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Surface conditions effect on energy exchange at the soil surface

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SURFACE CONDITIONS EFFECT ON ENERGY EXCHANGE AT THE SOIL SURFACE

Iowa State University

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Surface conditions effect on energy exchange at the soil surface

by

Kenneth Neil Potter

A Dissertation Submitted to the

Graduate Faculty in Partial Fulfillment of the

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GENERAL INTRODUCTION

Soil surface conditions affect many physical processes occurring in the soil. Plants respond to change in the soil temperature, soil strength, and soil atmosphere. The soil surface influences these parameters by affecting the absorption and partitioning of energy, the infiltration and evaporation of water, and the exchange of gases with the soil atmosphere. This is fortunate as the surface soil is the soil layer most easily modified by tillage. Often the farmer has conflicting objectives: trying to create a soil environment favorable for crop growth while reducing or eliminating soil erosion. To obtain these objectives, farmers have adopted many conservation tillage practices: no-till, ridge-till, strip -till, mulch-till, and reduced-till. Each of these management practices results in a different surface condition than that which occurs with the moldboard plow system. The increase in tillage options has made it important to understand physical processes occurring at the soil surface and the effect of different tillage practices on these processes.

Tillage research has been on-going for many centuries but has yielded mostly qualitative observations because there were often poor theoretical foundations to guide the collection and use of quantitative observations. The lack of theory and mathematical quantification has limited the inferences which can be drawn from creating a given soil condition. For example, collecting soil temperature data without regard to time or soil depth may result in misleading conclusions regarding tillage effects on soil temperature. The mechanism controlling the physical processes should be identified. Then, one may develop management systems to create the optimum soil environment for crop growth and still reduce erosion and maintain the soil resource.

The over all objectives of the research discussed in this dissertation were to identify mechanisms by which the soil surface layer affects solar radiation absorption, soil heat flux and soil temperature. The results of two studies will be discussed.

Study 1: 'Tillage effects on soil thermal properties', discusses parameters affecting heat flow and soil temperature. A comparison of soil thermal properties for three widely used tillage systems is presented. The importance of soil thermal properties in determining soil temperature and heat flux is also discussed.

Study 2: 'Soil surface roughness effects on radiation absorption and heat flux', discusses the effect of soil surface roughness on solar radiation reflectance, net radiation, and partitioning of energy at the soil surface.

Explanation of Dissertation Format

This dissertation has been prepared using the alternate format option available at Iowa State University. The dissertation contains a general introduction, a general literature review, two major sections, a general summary and discussion, a general list of literature cited, and appendices.

The two major sections are presented as complete typescripts of papers to be submitted to an appropriate scientific journal.

LITERATURE REVIEW

Soil temperature is a function of the net amount of heat that enters or leaves the soil and of the thermal properties of the soil. The amount of heat available to heat the soil depends on incoming radiation and the partitioning of energy at the soil surface. Soil thermal properties affect the transport and storage of heat within a given soil layer. This section will review literature on the influence of the surface soil layers on energy partitioning and heat transport. Specific topics include the radiation balance equation, surface effects on reflectivity, and soil thermal properties.

Radiation Balance

Solar radiation is the primary source of heat influencing soil temperatures (Rosenberg et al., 1983). Solar radiation is generally shortwave radiation occurring in the 300 to 4000 nm wavelengths. After reaching the soil surface, solar radiation may be either reflected or absorbed by the soil. The shortwave radiation is offset by the thermal or longwave radiation with wavelengths >4000 nm emitted by the soil. The difference between the absorbed and emitted radiation is the net radiation (R_n). These processes are summarized by the radiation balance equation:

$$R_n = (1 - r)\, R_s + R_l - \varepsilon\sigma T_s^4 \qquad (1)$$

where r is the reflection coefficient for shortwave radiation, R_s is incoming shortwave radiation, R_l is the incoming longwave radiation, ε is the soil emittance, σ is the Stefan-Boltzmann constant, and T_s is the surface temperature. Therefore, R_n is influenced both by surface reflection and emitted longwave radiation.

Net radiation is the energy available to heat the soil, evaporate water and heat the air. The energy balance at the soil surface is often summarized as

$$R_n = G + S + LE \qquad (2)$$

where G, S, and LE are the soil, sensible and latent heat fluxes, respectively.

Surface Reflection

The reflection coefficient (r) in Eq. 1 is defined as the ratio of radiant energy reflected to the total incoming shortwave radiation. Reflectance varies for different wavelengths of incoming solar radiation. Extensive work has been done in the area of remote sensing to identify soils by the reflection spectra (Thompson et al., 1983; Stoner and Baumgardner, 1981; Cipra et al., 1980). Differences in spectral reflectance have been correlated with organic matter content, particle size distribution, soil structure, iron oxide content, soil mineralogy, and parent material (Angstrom, 1925; Baumgardner et al., 1970; Bowers and Hanks, 1965; Bowers and Smith, 1972; Karmonov, 1970; Lindberg and Snyder, 1972; Mathews et al., 1973;

Stoner et al., 1980; Stoner and Baumgardner, 1981; Peterson et al., 1979; Shields et al., 1968).

Reflectance is also known to vary with soil water content, surface residue cover, and surface roughness. It is with these parameters that the greatest opportunities for affecting radiation absorption lie. Reflectance has been shown to decrease with increasing moisture content (Bowers and Hanks, 1965; Cipra et al., 1971; Peterson et al., 1979; Idso and Reginato, 1974). Idso et al., (1975) demonstrated the large increase in reflectance which occurs with drying. The greatest change in reflectance occurred rapidly during a significant color change as the soil dried. Idso et al. (1975) normalized the reflectance to eliminate solar zenith angle effects. The normalized albedo was described as a linear function of the volumetric water content of the upper (0.0-0.2 cm) soil layers. Graser and Van Bavel (1982) examined soil reflectance as a function of the soil water pressure potential. Reflectance was described as a step function, remaining relatively constant with decreasing moisture potential until a critical value of water potential was reached. Reflectance then increased rapidly with decreasing moisture potential until a new plateau was reached.

Surface residue cover can greatly influence the reflectivity of a soil (Hay et al., 1978; Van Doren and Allmaras, 1978; Gausman et al., 1977; Stoner et al., 1980). Von Hoyningen-Huene (1971) determined that the reflectance from a fresh straw cover was about twice the reflectance of a bare loamy sand. The difference in reflectance decreased in an exponential manner with time until, after six months, only a six-percent difference existed. Gausman et al. (1975) demonstrated that the orientation of the residue cover is important. Standing sugarcane residue reduced surface reflectance below that of a bare soil while littered or flat residue increased soil surface reflectance. The depth of residue cover was not as important as the percentage cover. Two dead corn leaves had nearly identical reflectance as a stack of eight dead corn leaves (Gausman et al., 1976).

Soil surface configuration or microrelief affects the reflectance of a soil (Allmaras, 1967). Coulson and Reynolds (1971) found that reflectance was increased 50% on a dry puddled Lola loam soil as compared to a dry disked condition. Radiation trapped in interstitial pore spaces was credited with the decrease in reflectance. Other authors have noted the decrease in reflectance with a roughened surface as compared to a smooth surface (Idso et al., 1975; Cipra et al., 1971; Gausman et al., 1977), although they did not quantify surface roughness. Allmaras et al. (1972) suggested that surface random roughness contributed more to the difference in radiation absorption than oriented roughness, such as that left by tillage implements. Random roughness was similar for chisel plow and moldboard plow treatments, but the chisel plow treatment included some oriented roughness, i.e., tillage marks. Estimated radiant flux density was similar for both treatments.

Arnfield (1975) suggested that differences in surface reflection coefficients could be due to multiple reflections between soil particles which effectively trapped radiation. This trapping process would be most efficient on rough surfaces and least effective on smooth surfaces. Several attempts to model roughness effects on reflectance have been based on the multiple reflection premise (Cruse et al., 1980; Linden, 1979). Predicted differences are generally small after the first reflection. Field data comparing reflectance over a range of roughness conditions is lacking, however.

Soil Thermal Properties

The thermal properties of a material determine the amount of heat stored in and transferred through a unit quantity of material. The general equation describing one demensional heat transfer in a homogeneous, isotropic medium is

$$\partial(C_v\ T)/\partial t = \partial(\lambda \partial T/\partial z)/\partial z \qquad (3)$$

where T is the temperature, t the time, z the depth, λ the thermal conductivity and C_v the volumetric heat capacity.

Volumetric heat capacity of a soil is defined as the change in heat content of a bulk volume of soil per unit change in temperature. Thermal conductivity is defined as the amount of heat transferred through a unit area in unit time under a unit temperature gradient. If both λ and C_v are assumed to be unchanged with time and depth, the classical heat flow continuity equation is formed

$$\partial T/\partial t = \alpha \partial^2 T / \partial z^2 \quad (4)$$

where α is the apparent thermal diffusivity defined as the ratio of thermal conductivity to volumetric heat capacity. Therefore, the thermal properties of a soil can be defined by the parameters: volumetric heat capacity, thermal conductivity and thermal diffusivity (Hillel, 1980).

The volumetric heat capacity of a soil can be calculated by the equation (de Vries, 1963)

$$C_v = X_s C_s + X_w C_w + X_a C_a \quad (5)$$

where X_s, X_w, and X_a are the volume fractions of solid, water and air and C_s, C_w, and C_a are the respective volumetric heat capacities. The $X_a C_a$ term is generally ignored. The solid component (X_s) is generally separated into mineral (X_m) and organic matter (X_o) volumetric contents. Substituting volumetric heat capacities into Eq. 5 results in

$$C_v = 1.9X_m + 2.5X_o + 4.2X_w \quad (6)$$

with C_v in units of MJ/m^3 K. Heat capacities have also been determined by calorimetry (Wierenga et al., 1969).

Soil thermal conductivity may be calculated directly by harmonic analysis of soil temperature data (Allmaras et al., 1977), alignment of null temperature gradient and heat flow (Kimball and Jackson, 1975) or line source heat-probe methods (de Vries and Peck, 1958; Wierenga et al., 1969). Thermal condúctivity may also be calculated from theoretical and physical considerations of soil parameters (de Vries, 1952). The de Vries method considers soil as a continuous medium of either water or air with ellipsoids of air and solids dispersed in it. The thermal conductivity is calculated by

$$\lambda = \sum_{i=1}^{n} k_i x_i \lambda_i / \sum_{i=1}^{n} k_i x_i \qquad (7)$$

where x_i is the volume fraction of the ith soil component, and λ_i is it's thermal conductivity. The k_i values are calculated from the thermal conductivities of the ith particle and of the continuous medium and from a shape factor of the ith particle (de Vries, 1952). The calculation procedure has been tested extensively and found to agree with measured values in some cases (de Vries, 1952; Wierenga et al., 1969; Sepaskhah and Boersma, 1979; Parikh et al., 1979). In other cases, a correction factor was necessary (Skaggs and Smith, 1967; Kimball et al., 1976; Hadas, 1977; Horton and Wierenga, 1984).

The apparent soil thermal diffusivity (α) determines to some extent the rate at which a soil warms or cools. Changes in both thermal conductivity and volumetric heat capacity affect α. Changes in soil water content affects both λ and C_v and can have large effects on α. At very low soil water contents, a small increase in the soil water content increases α because λ is increased more than C_v. Additional water has less effect on λ but continues to increase C_v. Therefore, α reaches a maximum value and declines with additional water. This was illustrated by van Duin (1956). Jackson and Kirkham (1958) found that real soil thermal diffusivity continued to increase until saturation occurred. However, the apparent diffusivity reached a maximum value at soil water contents less than saturation.

Independent measurements of C_v and λ may be used to calculate α. Other methods of calculating α include harmonic analyses and numerical techniques which use iterative procedures to match measured soil temperatures and calculated temperature values based upon the heat flow equation (Allmaras, 1977; Carson, 1963; Hanks et al., 1971; Wierenga et al., 1969; Asrar and Kanemasu, 1983). Horton et al., (1983) discussed six methods to calculate α from soil temperature measurements at a variety of soil depths and time increments. Results varied with the method used, but harmonic analysis with measurements every 1 to 2 h was recommended to determine α near the soil surface.

SECTION I. TILLAGE EFFECTS ON SOIL THERMAL PROPERTIES

ABSTRACT

Theoretical considerations indicate soil thermal properties may be altered by tillage, but few field studies have been conducted to compare soil thermal properties as affected by conservation or no-till management systems. Surface-soil thermal properties were determined in the row zone for three soils in three tillage systems: conventional till, chisel plow, and no-till. The apparent thermal diffusivity was determined by harmonic analysis of soil temperature data, volumetric heat capacity from the volume fraction of the soil components, and thermal conductivity by the line source heat-probe method.

Soil volumetric heat capacity was similar for all tillage treatments. Thermal diffusivity was significantly greater in the no-till system than in conventional and chisel plow tillage systems, indicating that thermal conductivity also was greater in the no-till system. Direct determination of thermal conductivity by the line source heat-probe method at one site indicated that thermal conductivity was more than 20% greater in no-till than in the conventional till system.

Percentage surface residue cover had a greater influence on soil temperature and soil heat flux than soil thermal properties.

INTRODUCTION

Tillage influences soil temperature by altering soil thermal properties, the surface configuration, and percentage surface residue cover. There have been many experiments concerning surface residue and surface configuration effects on soil temperature. For a review, see Willis and Amemiya (1973) and Voorhees et al. (1981). The general consensus is that spring soil temperatures are reduced with increasing amounts of surface residue. There is evidence, however, that the use of ridge planting may reduce differences in soil temperature between tillage systems while maintaining surface residue cover (Radke, 1982).

The increasing interest in computer modeling of tillage effects on soil temperature makes knowledge of soil thermal properties important (Cruse et al., 1982). Van Duin (1956) discussed the theoretical implications of tillage on soil thermal properties. Decreasing soil porosity or increasing soil water content increased thermal conductivity (λ). Soil heat flux was reduced by loosening the surface soil layer.

Tillage effects on soil thermal properties have been considered in only a few field studies. Thermal diffusivity (α) was larger in a direct-drilled barley field as compared with a plowed field throughout the growing season in England (Hay et al., 1978). The difference in α was attributed to the greater soil bulk density in the direct-drilled field. Allmaras et al. (1977) found λ increased with increasing amounts of secondary tillage following plowing.

With the wide variety of tillage systems available, it is important to understand the effect of tillage on physical properties and processes occurring in the soil. The objective of this study was to determine the effect of widely used tillage systems on soil thermal properties for a variety of soils. Soil heat flux also was determined to compare the effects of ridged and flat no-till systems with other tillage systems.

THEORETICAL BACKGROUND

The method of determining α, λ, and soil heat flux used in this study is based upon solutions to the heat conduction equation. A brief review of the concepts involved is presented.

An equation describing one-dimensional heat transfer in a homogeneous media is:

$$\partial C_v T/\partial t = \partial(\lambda \partial T/\partial z)/\partial z \tag{1}$$

Where T is the temperature, t is the time, z the depth, C_v the volumetric heat capacity, and λ the apparent thermal conductivity. Assuming that C_v and λ are independent of depth and time, equation (1) may be rewritten as:

$$\partial T/\partial t = \alpha \ \partial^2 T/\partial z^2 \tag{2}$$

where α is the apparent thermal diffusivity ($\alpha = \lambda/C_v$).

With boundary conditions

$$T(o,t) = \bar{T} + \sum_{n=1}^{m} A_{on} \sin (n\omega t + \phi_{on}) \tag{3}$$

and

$$\lim_{z \to \infty} T(z,t) = \bar{T} \tag{4}$$

the solution to Eq. (2) to describe temperature with depth and time (Carslaw and Jaeger, 1959) is:

$$T(z,t) = \bar{T} + \sum_{n=1}^{m} [A_{on} \exp(-z\sqrt{n\omega/2\alpha}) \sin(n\omega t + \phi_{on} - z\sqrt{n\omega/2\alpha})] \tag{5}$$

where $\bar{T}$ is the temporal average soil temperature, assumed to be equal at all depths; m is the number of harmonics; A_{on} and ϕ_{on} are the amplitude and phase angle, respectively, of the nth harmonic for the upper boundary temperature and ω the radial frequency equal to $2\pi/P$, with P being the period of the fundamental cycle. The value of α can be solved implicitly from Eq. (5) if temperature measurements are available at one depth in addition to those at the upper boundary. The value of α is selected to minimize the sum of squared differences between calculated (Eq. (5)) and measured temperature values (Horton et al., 1983).

The soil heat flux can be obtained by the equation:

$$G = -\lambda(\partial T/\partial z) \tag{6}$$

where G is the soil heat flux. The temperature gradient with depth is obtained by differentiating Eq. (5) with respect to z resulting, after simplification, in:

$$\partial T(z,t)/\partial z = \sum_{n=1}^{m} -A_{on} \sqrt{n\omega/\alpha}\ \exp(-z\sqrt{n\omega/2\alpha}) \sin[n\omega t + \phi_{on} + \pi/4 - z\sqrt{n\omega/2\alpha}] \tag{7}$$

With $\lambda = \alpha C_v$, substituting Eq. (7) into Eq. (6), results in an expression for the soil heat flux at all depths and times (Horton and Wierenga, 1983):

$$G(z,t) = \sum_{n=1}^{m}\{A_{on}C_v\sqrt{n\omega\alpha}\ \ \exp(-z\sqrt{n\omega/2\alpha})\ \sin(n\omega t + \phi_{on} + \pi/4 - z\sqrt{n\omega/2\alpha})\} \tag{8}$$

The soil heat flux is assumed positive downward in Eq. (8).

Thermal conductivity is frequently determined by the line source heat probe method. In this method, Eq. (1) is rewritten for cylindrical coordinates as

$$C_v\ \partial T/\partial t = (\lambda/r)\partial(r\ \partial T/\partial r)/\ \partial r \tag{9}$$

where r is the radial coordinate. For a constant line heat source (q), an infinite medium and a uniform initial temperature (T_o) of the probe and its surrounding medium, the solution to Eq. (9) is (Carslaw and Jaeger, 1959)

$$T_p - T_o = (q/4\pi\lambda)[-E_i(-r^2/4\alpha t)] \tag{10}$$

for a heating cycle where T_p is the temperature at the probe and E_i is the exponential integral. For all but the smallest times, Eq. (10) expands to

$$T_p - T_o = (q/4\pi\lambda)[-\gamma + \ell n(4\alpha/r^2) + \ell n(t)] \tag{11}$$

where γ is the Euler constant. By plotting $T_p - T_o$ vs. $\ell n(t)$, one should obtain a straight line with a slope (b) of $q/4\pi\lambda$. Because $q = I^2R$, with I the uniform current applied to the probe and R the resistance per unit length of the probe,

$$\lambda = I^2R/4\pi b \tag{12}$$

The solution to Eq. (9) for the cooling cycle is (de Vries and Peck, 1958)

$$T_p - T_o = (q/4\pi\lambda)\ \ell n[t/(t-t_o)] \tag{13}$$

where t_o is the time heating ended. Plotting $T_p - T_o$ vs. $\ell n[t/(t-t_o)]$, one should obtain a straight line with a slope of $q/4\pi\lambda$. The thermal conductivity is then calculated by Eq. (12). An example of the graphical method of calculating λ by the line source heat-probe method is presented in Fig. 1.

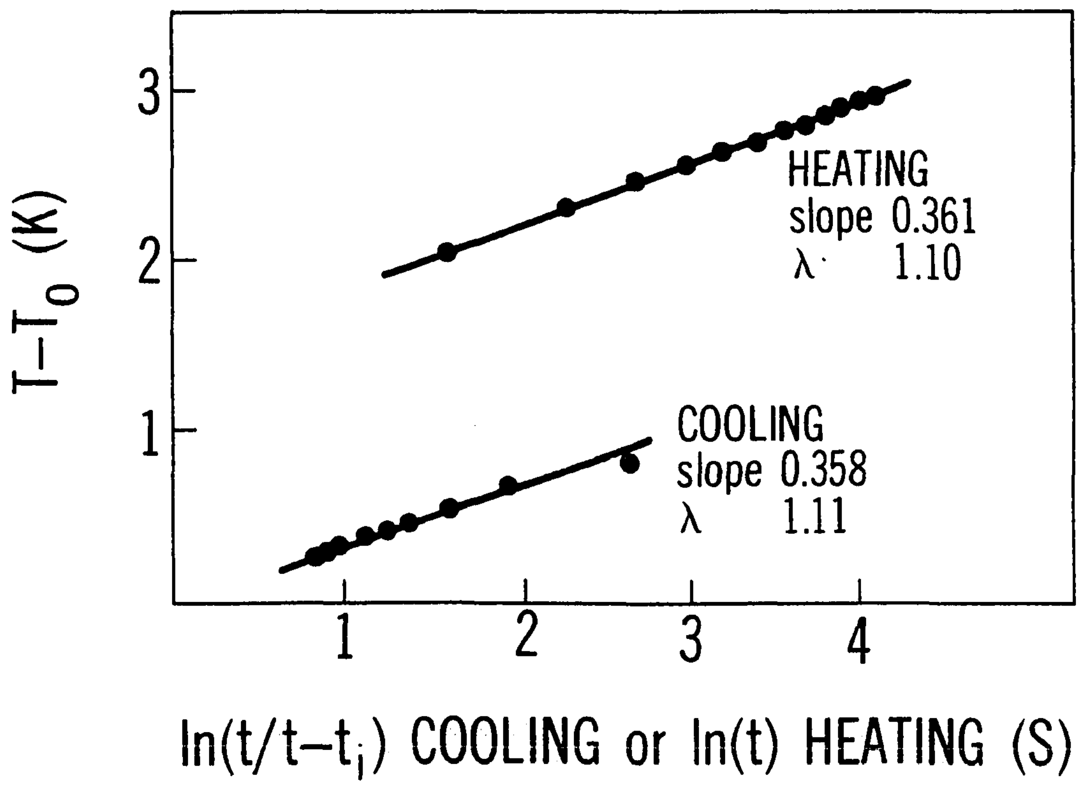

Figure 1. An example of the calculation of thermal conductivity (λ) by the line source heat-probe method. The heating current was 0.19 A, and the probe resistance was 1.38 ohms/cm

MATERIALS AND METHODS

Soil tillage plots established for at least 3 years in three locations in Iowa were utilized for this work. The plots were located at the Northwest Research Center near Sutherland, IA; the Northeast Research Center near Nashua, IA; and the Agronomy and Agricultural Engineering Research Center near Ames, IA. Soils at the respective sites were Galva silt loam (fine-silty, mixed, mesic, Typic Hapludoll), Readlyn (fine-silty, mixed, mesic, Aquic Hapludoll) and Nicollet (fine-silty, mixed, mesic, Aquic Hapludoll). Tillage treatments were arranged as randomized complete blocks with two replications at each site.

The three tillage systems studied included no-tillage, chisel plow, and conventional tillage. The conventional tillage system refers to fall moldboard plow followed by spring disk. The chisel-plow treatment was fall chisel plow followed by spring disk. The Ames no-tillage treatment was a ridge-plant system where corn was planted on ridges established in June of the year preceding the study. The other no-tillage systems were not ridged. Copper-constantan thermocouples were placed at depths of 0.025, 0.05 and 0.15 m in the row after corn planting at two locations in each plot. Temperatures were recorded hourly at all sites in 1983 and every 2 h at the Ames site in 1982 by automatic data logging equipment (Campbell CR5, Logan, Utah[1]). Selected

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[1]Trade and company names are included for the benefit of the reader and do not imply endorsement or preferential treatment of the product by Iowa State University.

dates were chosen for analysis using the criteria that the corn had not emerged; the weather was mostly sunny; and several consecutive rain free days had occurred which allowed establishment of the harmonic heat flow relationships.

A Fourier series of m = 5 harmonics was fitted to observed temperatures at the 0.025-m depth for all treatments to determine values of A_{on} and ϕ_{on}. Temperature values from three measurements before and after the day of interest were included in the analysis to improve estimates of heat flux near the beginning and end of the day (Horton and Wierenga, 1983). The daily mean apparent thermal diffusivity of each treatment was determined implicitly by fitting Eq. (5) to the 0.15-m soil temperature.

Volumetric heat capacity (C_v) was calculated by de Vries (1963) equation:

$$C_v = 1.92\ X_m + 2.51\ X_o + 4.18\ X_w \qquad (\mathrm{M\ J/m^3\ K}) \qquad (14)$$

where X_o, X_m, and X_w are the volume fractions of organic matter, mineral, and water of the soil, respectively. Soil water content of the surface 0.15-m of soil was determined gravimetrically between 1400 and 1500 h on the day of interest. Soil bulk density at the 0.025 to 0.101 m depth was determined from the mean of three undisturbed 0.076 by 0.076 m diameter core samples taken from the row near the thermocouple installation.

Soil thermal property data from selected days were analyzed statistically by using a randomized complete-block design. Because α determinations were based on hourly or bi-hourly soil temperatures measured at fixed thermocouple positions, error autocorrelations in α determinations on sequential days were a concern. The error autocorrelation would reduce the validity of the statistical analysis performed on the tillage treatment effects on α. Therefore, data for a single day at each site were statistically analyzed to avoid autocorrelation of errors.

Values of thermal conductivity (λ) were determined by the line source heat-probe method in the no-till and conventionally tilled treatments over a range of moisture conditions at the Ames site in 1983. Line source heat-probes 0.195 m long and 0.001 m in diameter were placed 0.08 m deep near the row. A 0.19 A current was applied for 60 s. Probe temperatures were recorded at 5-s intervals during the heating and cooling cycles. Measurements were taken for a minimum of three heating and cooling cycles at each location and sample date. Probe temperature values were corrected for existing transient soil temperature conditions (Jury and Bellantuoni, 1976). The slopes of T_p-T_o vs. $\ell n(t)$ and T_p-T_o vs. $\ell n\ [t/(t-t_o)]$ were determined by linear regression and λ was calculated by Eq. (12). Values of λ determined by heating and cooling cycles were averaged. Volumetric heat capacity was determined by Eq. (14). Thermal diffusivity was calculated from the ratio of λ determined by the line source heat probe and C_v.

Soil heat flux was calculated at the 0.025-m depth by using Eq. (8) and calculated values of C_v. Values of A_{on} and ϕ_{on} were obtained by fitting a Fourier series to the 0.025-cm soil temperature (Eq. 3). Thermal diffusivities were determined by Eq. (5).

Percentage surface residue cover was determined for five locations in each plot by a photographic method similar to that used by Williams (1979). All plots had been planted to corn the previous year.

RESULTS AND DISCUSSION

Soil Thermal Properties

Temperature values at the 0.025-m depth for each treatment were fitted to Eq. (3), and Eq (5) and the 0.15-m depth soil temperature was used to calculate the apparent thermal diffusivity (α) for each tillage treatment. Results for the Ames site in 1983 are presented in Fig. (2). Thermal diffusivity decreased linearly in all tillage treatments as the volumetric water content (Θ) increased. Other studies have shown that at low water contents, α increases with an increase in Θ, but reaches a maximum then decreases with further increase in Θ (van Duin, 1956). The range in water content was less in the no-till treatment than in the conventional or chisel plow treatments, but for all measured soil water contents, no-till had a larger α than either conventional or chisel plow. There was very little difference between the conventional and chisel plow treatments.

Mean diurnal values of α for each site and tillage treatment are presented in Table 1. Mean values of α across sites were 4.39, 3.56, and 5.22 x 10^{-7} m^2/s for the conventional tillage, chisel-plow, and no-tillage treatments, respectively. Analysis of variance showed significant ($P = 0.05$) differences in α between tillage systems. Orthogonal contrasts showed that the no-tillage system had a significantly ($P = 0.05$) different α from the other tillage systems. Differences between conventional-tillage and the chisel plow treatment were not significantly different.

An analysis of soil properties that could influence α was

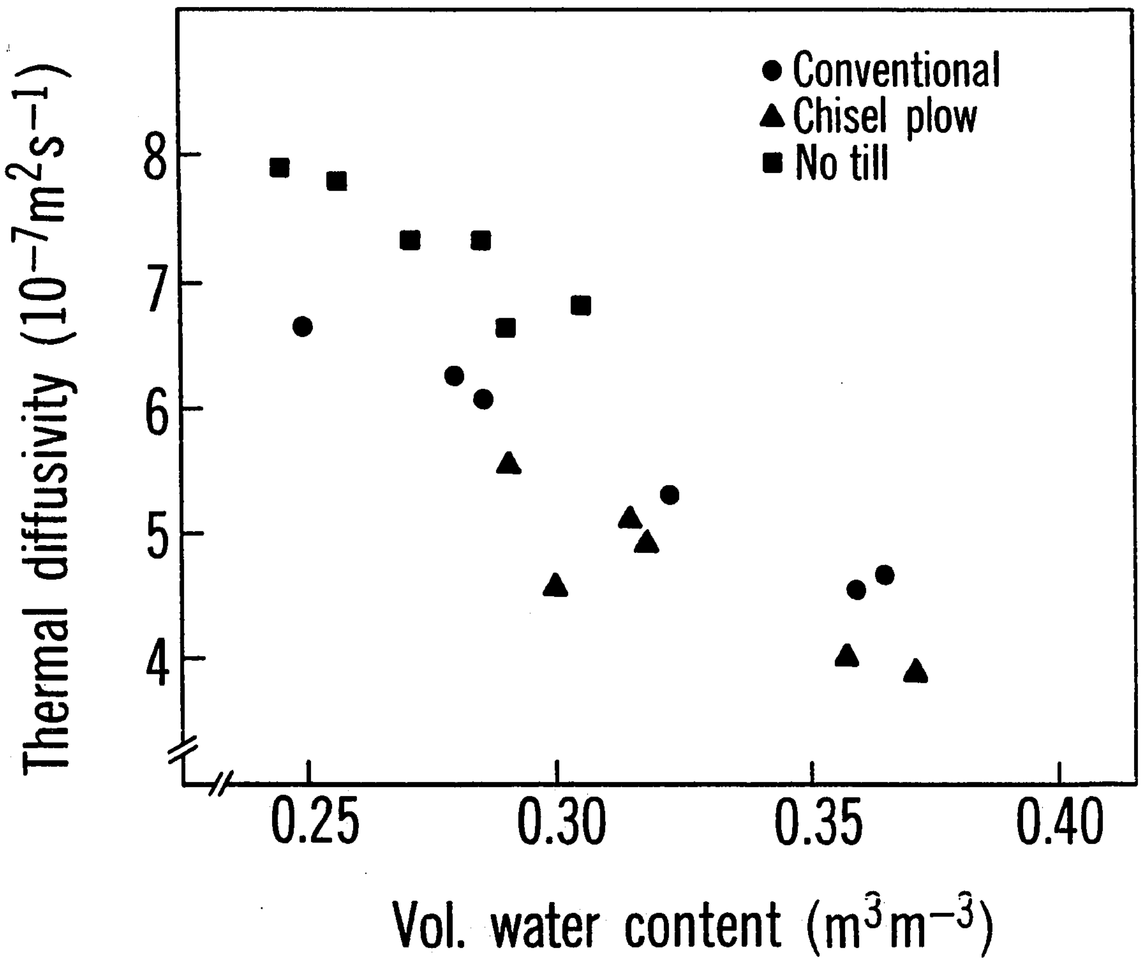

Figure 2. The apparent thermal diffusivity (α) determined by the harmonic method for three tillage systems at Ames, IA in 1983

Table 1. Apparent thermal diffusivity and volumetric heat capacity of soil in the row after planting

Site	Apparent thermal diffusivity (10^{-7} m^2/s)[a]			Volumetric heat capacity (MJ/m^3 K)[b]		
	Conventional	Chisel plow	No-till	Conventional	Chisel plow	No-till
Ames 1983	5.14 2.25	4.53 0.81	6.86 0.87[c]	2.24 0.32	2.42 0.06	2.14 0.10[c]
Nashua	3.73 0.56	3.38 0.14	3.91 1.98	2.34 0.10	2.39 0.05	2.51 0.13
Sutherland	4.52 1.69	3.14 0.08	5.40 2.10	2.49 0.19	2.46 0.04	2.48 0.09
Ames 1982	3.20 0.74	3.21 0.62	4.73 2.67[c]	2.19 0.18	2.32 0.18	2.24 0.06[c]

[a]Mean ± 1 standard deviation, n = 4.

[b]Mean ± 1 standard deviation, n = 6.

[c]Ridged.

conducted; i.e., soil water content and soil bulk density. Mean soil water content and bulk density values are presented in Table 2. Soil water content ranged from 0.26 to 0.38 m^3/m^3 with most of the variance occurring between sites. Analysis of variance showed no significant differences ($P = 0.05$) in soil volumetric water content among tillage treatments. However, average soil water content was 0.01 to 0.06 m^3/m^3 lower in the ridge no-till system compared with the conventional till and chisel-plow till systems. Soil bulk density ranged from 1.21 to 1.40 Mg/m^3. Again, analysis of variance showed no significant differences between bulk density values of three tillage systems. Tillage effects on bulk density have been shown to vary between soils. Some researchers have found little difference in bulk density due to tillage (Blevins et al., 1983), while others found reductions in bulk density after tillage (Gantzer and Blake, 1978).

Soil volumetric heat capacity (C_v) was calculated for all tillage treatments. Values ranged from 2.14 to 2.51 MJ/m^3 K (Table 1). Analysis of variance did not show significant differences between tillage treatments. Because C_v was similar among tillage treatments and α varied, differences in thermal conductivity (λ) due to the tillage treatment were likely.

Independent determinations of λ were made using the line source heat-probe for the conventional tillage and no-tillage treatments at the Ames site in 1983 (Fig. 3). Thermal conductivity was >20% larger in the no-tillage system than in the conventionally tilled system at all soil water contents. Soil water contents ranged from 0.20 to 0.35 m^3/m^3 in

Table 2. Soil volumetric water content and soil bulk density measured in the row after planting for three tillage systems

Site	Volumetric water content (m^3/m^3)[a]			Bulk density (Mg/m^3)[b]		
	Conventional	Chisel plow	No-till	Conventional	Chisel plow	No-till
Ames 1983	0.31 0.07[c]	0.34 0.03	0.28 0.01[d]	1.25 0.09	1.32 0.12	1.28 0.11[d]
Nashua	0.30 0.02	0.34 0.02	0.37 0.05	1.28 0.08	1.38 0.12	1.27 0.11
Sutherland	0.37 0.03	0.37 0.02	0.38 0.03	1.23 0.08	1.21 0.09	1.25 0.06
Ames 1982	0.27 0.03	0.30 0.07	0.26 0.04[d]	1.33 0.12	1.26 0.14	1.40 0.09[d]

[a] 2.5 to 15 cm depth, n = 6.

[b] 2.5 to 10.1 cm depth, n = 6.

[c] Mean ± 1 standard deviation.

[d] Ridged.

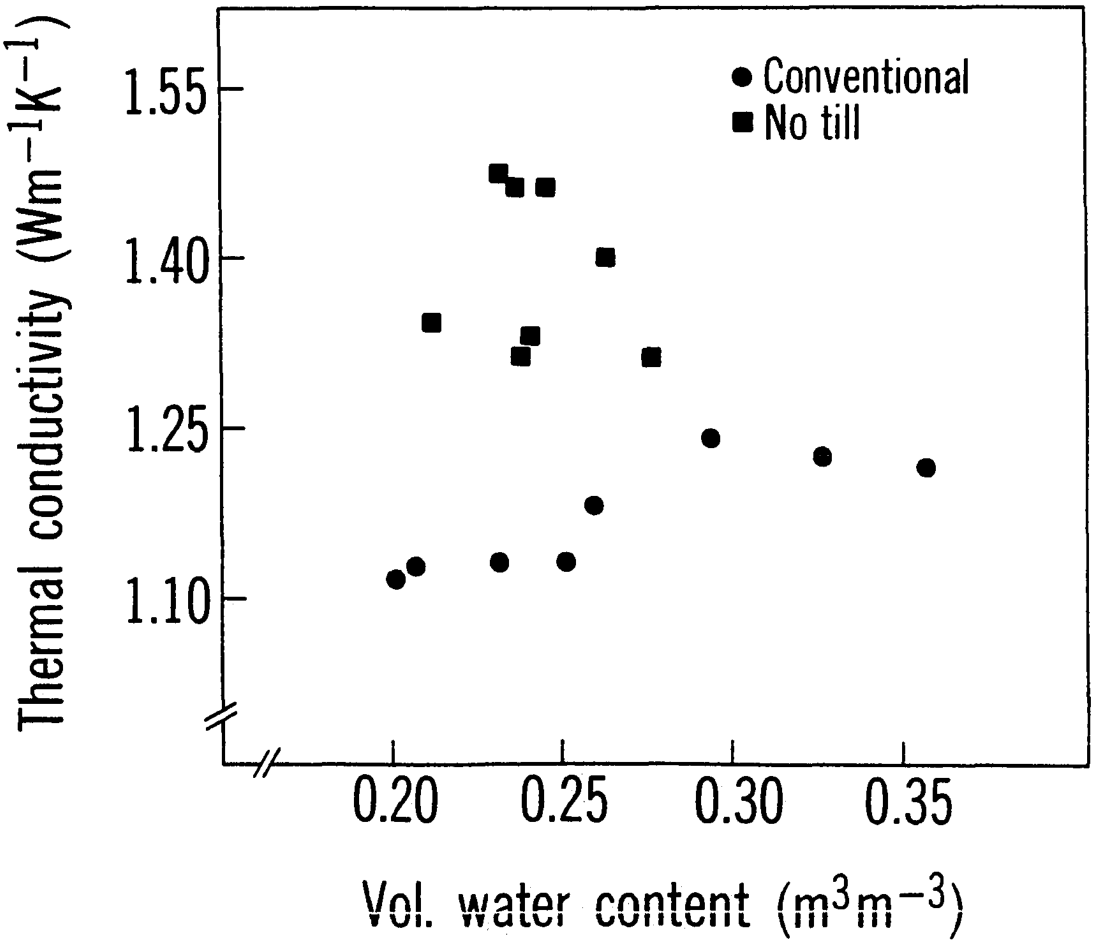

Figure 3. Thermal conductivity determined by the line source heat-probe for two tillage systems at Ames, IA in 1983.

the conventional tillage and 0.21 to 0.28 m^3/m^3 in the no-tillage treatments at the time these measurements were made. Volumetric heat capacity was calculated by Eq. (14), and α was calculated. Thermal diffusivity calculated by this method was also greater in the no-tillage soil than in the conventionally tilled soil (Fig. 4). Differences in C_v were due to differences in soil water content because the volumetric fraction of mineral and organic matter were not different. The volumetric heat capacity was changed more than the thermal conductivity by the change in soil water content. Consequently, in this range of soil water contents, λ increased with increasing soil water content while α decreased as soil water content increased. This was also observed by de Vries (1975) for loam soils at >0.12 volumetric moisture content.

A comparison of α calculated by the harmonic method and the line source heat-probe method is not strictly valid, but is still of interest. Thermal diffusivity calculated from the line source heat-probe data was slightly lower than that calculated by Eq. (5) for similar moisture conditions: 5.37×10^{-7} vs. 6.14×10^{-7} m^2/s in the conventional tillage and 6.46×10^{-7} vs. 6.79×10^{-7} m^2/s in the no-tillage system for the line source heat-probe and harmonic methods, respectively. Overall, the agreement of the two methods was quite good but there are several reasons that the two methods may not yield identical results. The harmonic method estimates α averaged over the diurnal cycle and a range of soil depths, i.e., 0.025- to 0.15-m. With the line source heat-probe method one calculates λ for a smaller volume

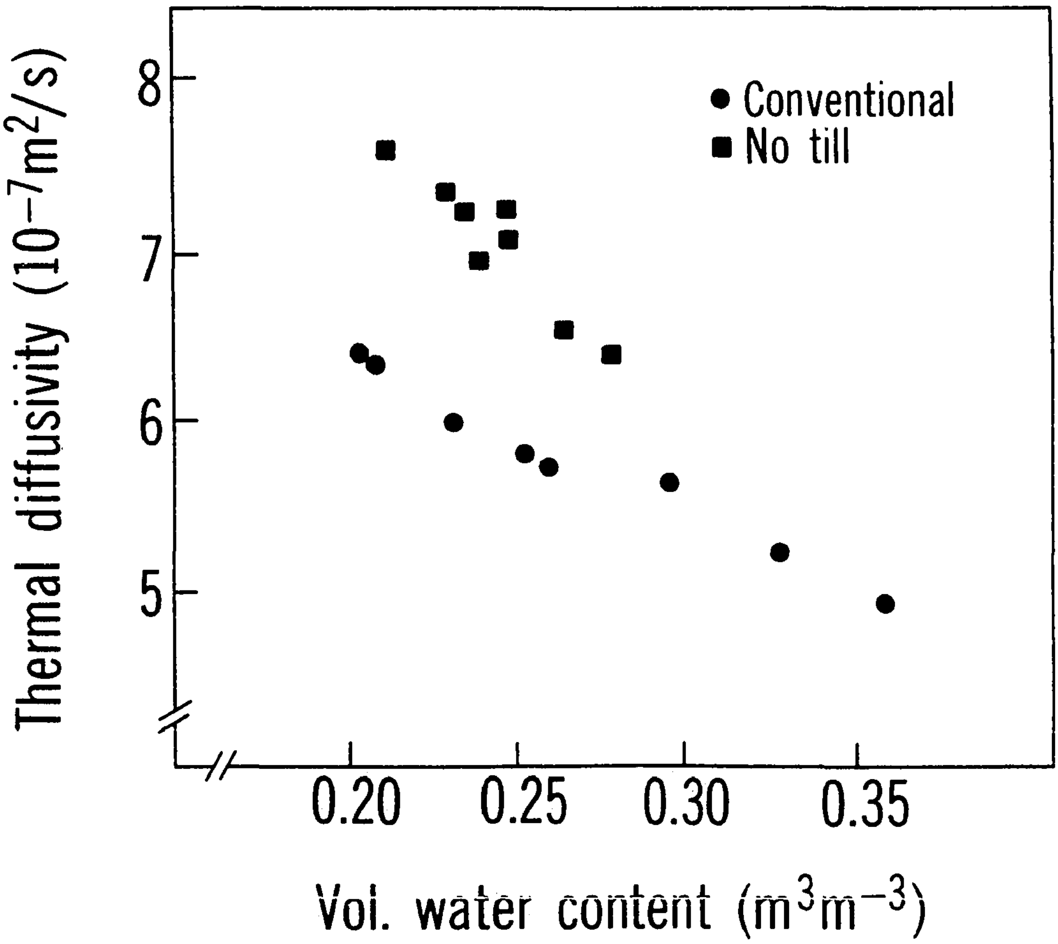

Figure 4. Thermal diffusivity determined from independent determinations of thermal conductivity and volumetric heat capacity.

of soil and a shorter time period. This λ is then used along with the measured C_v to calculate α. Possible reasons that the line source heat-probe values of α were lower than the values determined by harmonic analysis are that the line source method may underestimate λ because of air entrapped at the surface of the heat-probe and the line-source method neglects the diurnal movement of heat by vapor distillation (Sepaskhah and Boersma, 1979).

Soil Temperature

Soil temperatures were recorded at 0.025-, 0.05- and 0.15-m depths at all sites. Clear sky conditions prevailed at the Ames (1983) and Sutherland sites during measurements. Occasional clouds were present at the Nashua and the Ames (1982) sites. Differences in maximum soil temperature among tillage treatments were evident, especially at the 0.025-m depth. Maximum soil temperatures were in the order, no-till < chisel plow < conventional till at the Nashua and Sutherland sites where a flat no-till system was used. Maximum soil temperatures were in the order, chisel plow < conventional till < no-till at the Ames site where a ridged no-till system was used. Representative temperature profiles are presented in Figs. 5 and 6, which illustrate the difference in no-till soil temperatures with and without ridging as compared with other tillage systems.

The soil temperature data illustrates the importance of the extent and spatial distribution of the surface residue cover. Percentage surface cover data are presented in Table 3. Residue cover ranged from 2 to 12% after conventional tillage, 20 to 55% after chisel plowing, and

Figure 5. Soil temperature at 0.025-, 0.05-, and 0.15-m depths for three tillage systems. The no-till system was a ridge-plant system

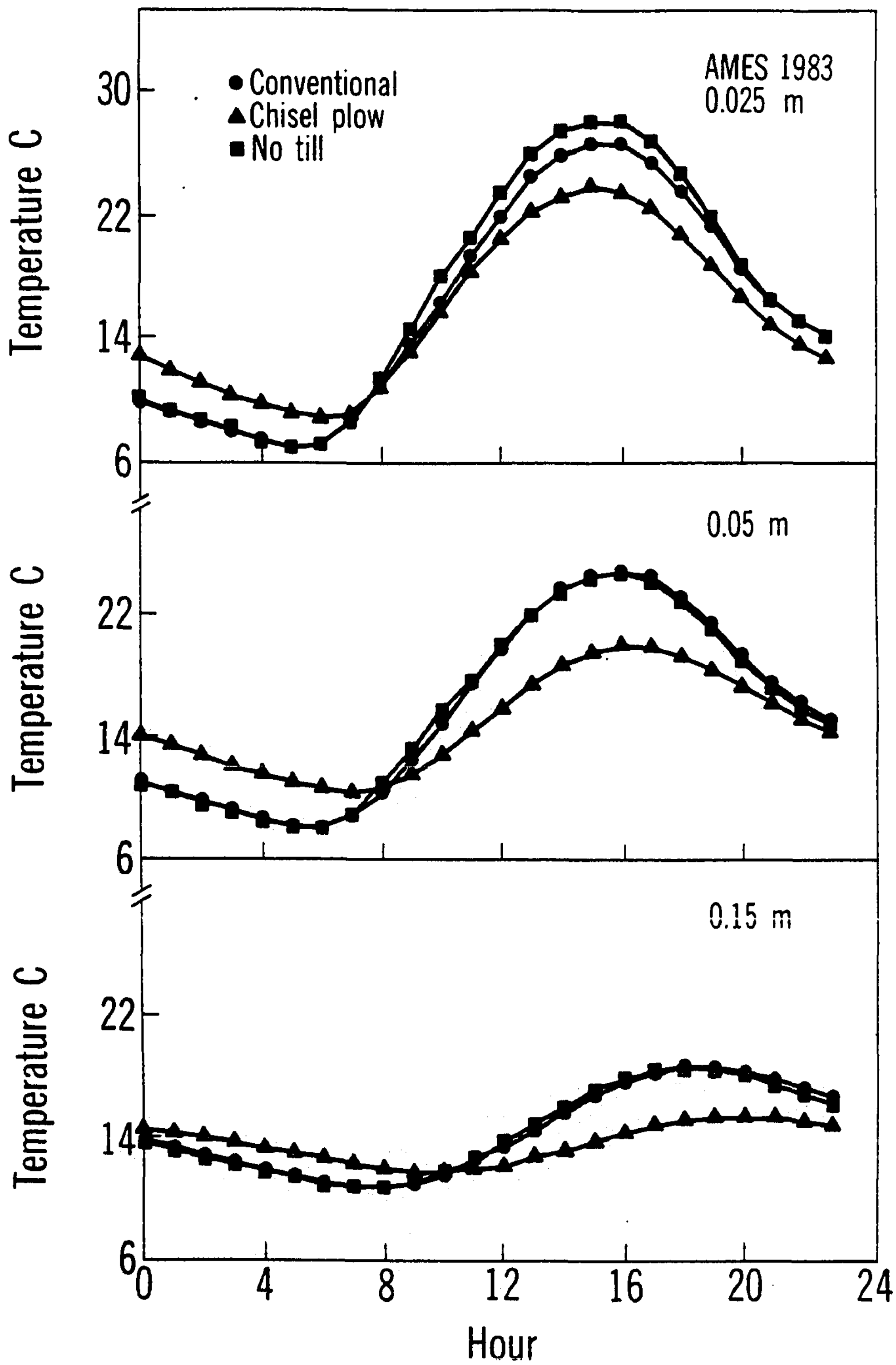
Conventional
Chisel plow
No till
AMES 1983
0.025 m
0.05 m
0.15 m
Temperature C
Temperature C
Temperature C
30
22
14
6
22
14
6
22
14
6
0
4
8
12
16
20
24
Hour

Figure 6. Soil temperature at 0.025-, 0.05-, and 0.15-m depths for three tillage systems. The no-till system was not ridged

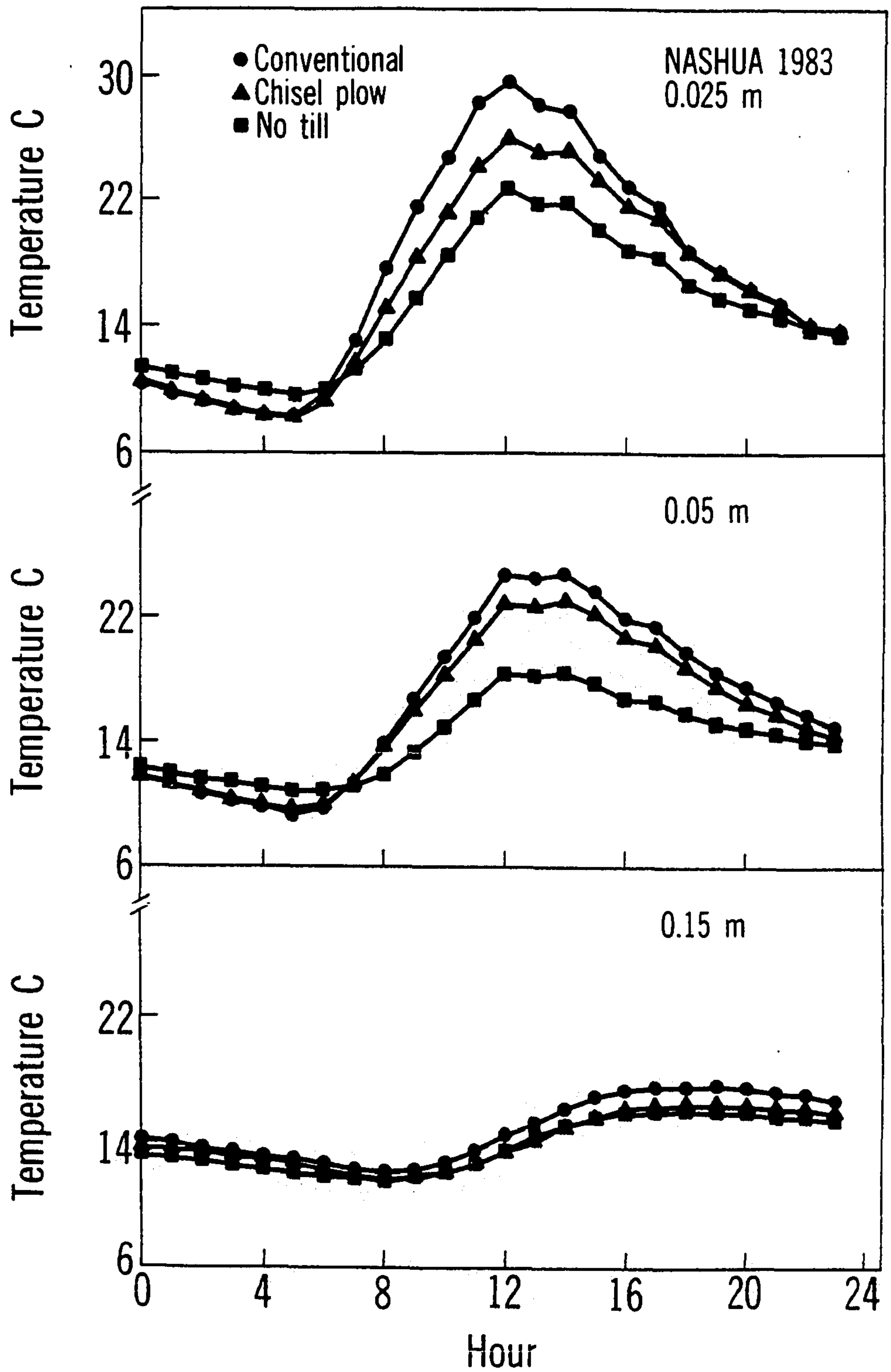
Conventional
Chisel plow
No till
NASHUA 1983
0.025 m
0.05 m
0.15 m
Temperature C
30
22
14
6
0
4
8
12
16
20
24
Hour

Table 3. Percentage surface residue cover remaining after tillage

Tillage	Percentage residue cover			
	Ames 1983	Nashua	Sutherland	Ames 1982
Conventional	5.9	9.4	12.5	1.8
Chisel plow	38.5	36.2	55.6	20.0
No-till	60.9	75.3	68.5	60.0

60 to 75% after planting with no-till. Maximum soil temperatures decreased with increasing residue cover at the Nashua and Sutherland sites where there were no observable patterns in residue distribution on the soil surface. At the Ames site, however, soil temperature in the row was not correlated with percentage residue cover. The no-till treatment with a high (60%) residue cover had soil temperatures similar to those of the conventional treatment with a low (2%) residue cover. Soil temperature was reduced in the chisel-plow treatment (20-35% residue cover). At the Ames site where the no-tillage soil had been ridged, the row was nearly bare of residue with almost all the residue concentrated in the interrow. Therefore, the temperature was not measured directly below crop residue. No residue distribution patterns were evident in the chisel plow treatment where soil temperature was depressed.

Soil Heat Flux

Soil heat flux at the 0.025-m depth in the row was calculated by Eq. (8) for all tillage treatments. Comparisons of soil heat flux among tillage treatments are presented in Figs. 7 and 8. The major difference between Fig. 7 and Fig. 8 lies in the relative amplitude of the soil heat flux of the ridged no-till vs. the flat no-till. With flat no-till (Fig. 7), soil heat flux amplitudes were in the order, no till < chisel plow < conventional till. With ridged no-till (Fig. 8), soil heat flux amplitudes were in the order chisel plow < conventional till < no-till. The combination of ridging and concentrating residue in the interrow in the no-till system increased the soil heat flux amplitude in the row above that observed in the conventional tillage system.

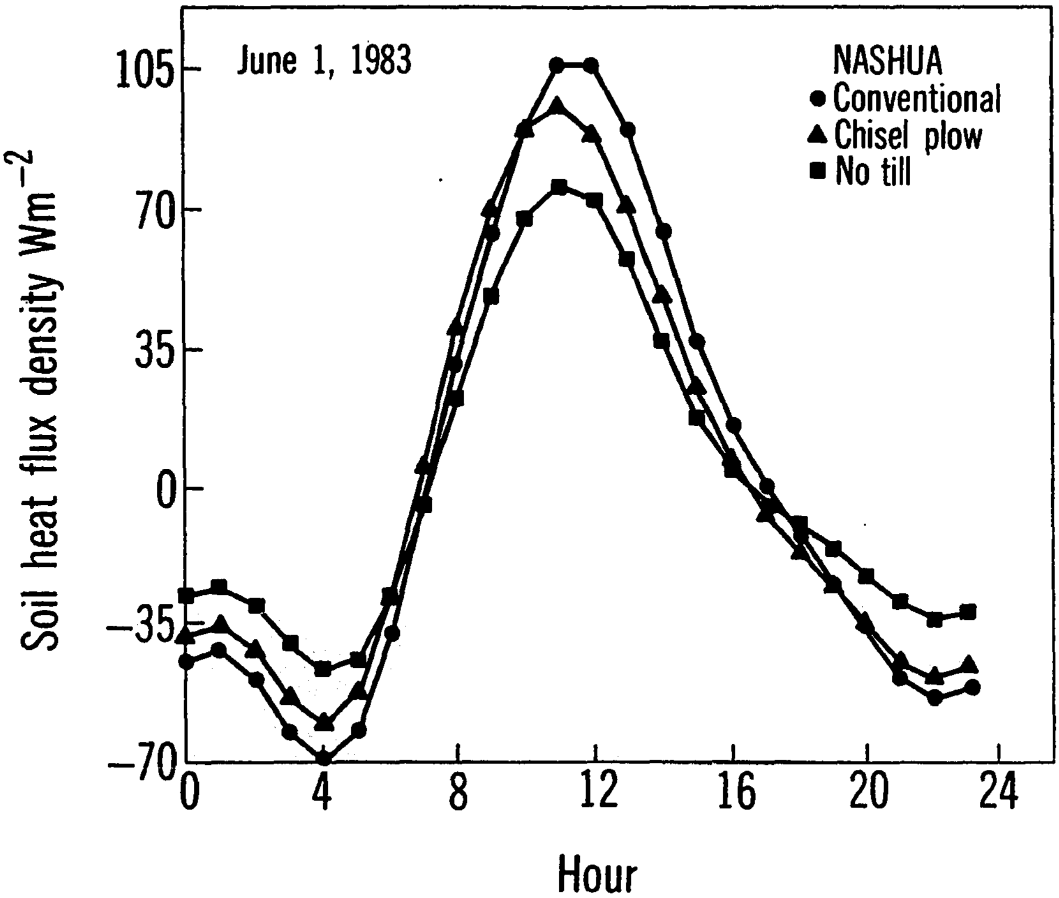

Figure 7. Representative soil heat flux density at the 0.025-m depth for three tillage systems. The no-till was not ridged

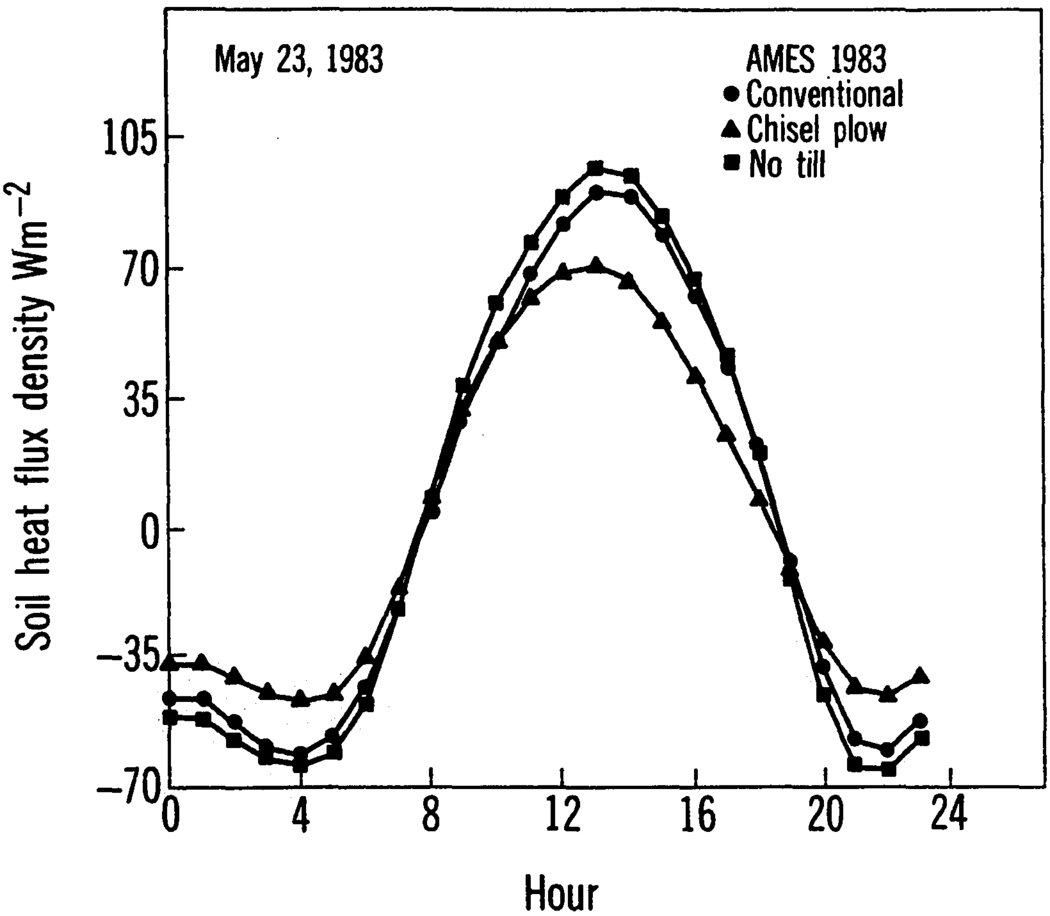

Figure 8. Representative soil heat flux density at the 0.025-m depth for three tillage systems. The no-till was a ridge-plant system

GENERAL DISCUSSION AND SUMMARY

Determination by the harmonic method indicates that tillage reduced the apparent soil thermal diffusivity, (α), in the row. Because the volumetric heat capacity, (C_v) in the row was similar in the three tillage systems in this study, the thermal conductivity (λ) must have been affected by tillage. This is supported by the independent determination of λ by the line source heat-probe method which showed λ to be more than 20% greater in the no-till soil than in the conventionally tilled soil. Also of interest is that the percentage total pore space and percentage air-filled pore space in the soil must have been similar among treatments because soil bulk density and volumetric water contents were not significantly different among treatments. This suggests that tillage produced a pore size distribution and/or soil matrix arrangement that was different from that occurring where no tillage was done. Although comparable volumetric quantities of water and solids may be found in soils tilled differently, mass transfer processes may be different; i.e., a simple measure of soil bulk density and water content may not be sufficient to identify tillage impacts on processes affecting the soil environment. Even though soil thermal properties in the row varied among tillage systems, percentage residue cover and distribution seemed to have the dominant effect on soil temperature and soil heat flux.

ACKNOWLEDGMENT

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LITERATURE CITED

Allmaras, R. R., E. A. Hallauer, W. W. Nelson, and S. D. Evans. 1977. Surface energy balance and soil thermal property modifications by tillage-induced soil structure. Minn. Agric. Exp. Stn. Tech. Bull. 306. 41 p.

Blevins, R. L., G. W. Thomas, M. S. Smith, W. W. Frey, and P. L. Cornelius. 1983. Changes in soil properties after 10 years continuous nontilled and conventionally tilled corn. Soil Tillage Res. 3:135-146.

Carslaw, H. S., and J. C. Jaeger. 1959. Conduction of heat in solids. 2nd ed. Oxford University Press, London. 509 p.

Cruse, R. M., K. N. Potter, and R. R. Allmaras. 1982. Modeling tillage effects on soil temperature. In Predicting Tillage Effects on Soil Physical Properties and Processes. Am. Soc. Agron., Soil Sci. Soc. Am. Spec. Publ. 44:133-150.

de Vries, D. A. 1963. Thermal properties of soils. Chapter 7. In W. R. van Wijk (ed.). Physics of the Plant Environment. North Holland Publ. Co., Amsterdam.

de Vries, D. A. 1975. Heat transfer in soils. pp. 5-28. In D. A. de Vries and N. H. Afgan (eds.). Heat and Mass Transfer in the Biosphere. Scripta Book Co., Washington, D. C.

de Vries, D. A., and A. J. Peck. 1958. On the cylindrical probe method of measuring thermal conductivity with special reference to soils. I. Extension of theory and discussion of probe characteristics. Aust. J. Phys. 11:225-271.

Gantzer, C. J., and G. R. Blake. 1978. Physical characteristics of the Le Seur clay loam soil following no-till and conventional tillage. Agron. J. 70:853-857.

Hay, R. K. M., J. C. Holmes, and E. A. Hunter. 1978. The effects of tillage, direct drilling and nitrogen fertilizer on soil temperature under a barley crop J. Soil Sci. 29:174-183.

Horton, R., and P. J. Wierenga. 1983. Estimating the soil heat flux from observations of soil temperature near the surface. Soil Sci. Soc. Am. J. 47:14-20.

Horton, R., P. J. Wierenga, and D. R. Nielsen. 1983. Evaluation of methods for determining the apparent thermal diffusivity of soil near the surface. Soil Sci. Soc. Am. J. 47:25-32.

Jury, W. A., and B. Bellantuoni. 1976. A background temperature correction for thermal conductivity probes. Soil Sci. Soc. Am. J. 40:608-610.

Radke, J. K. 1982. Managing early season soil temperatures in the northern Corn Belt using configured soil surfaces and mulches. Soil Sci. Soc. Am. J. 46:1067-1071.

Sepaskhah, A. R., and L. Boersma. 1979. Thermal conductivity of soils as a function of temperature and water content. Soil Sci. Soc. Am. J. 43:439-444.

van Duin, R. H. A. 1956. On the influence of tillage on conduction of heat, diffusion of air and infiltration of water in soil. Versl. Landbouwkd. Onderz. Agric. Res. Rep. No. 62.7:82.

Voorhees, W. B., R. R. Allmaras, and C. E. Johnson. 1981. Alleviating temperature stress. pp. 215-266. In G. F. Arkin and H. M. Taylor (eds.). Modifying the Root Environment to Reduce Crop Stress. Am. Soc. Agric. Engr., St. Joseph, Michigan.

Williams, T. H. Lee. 1979. An error analysis of the photographic technique for measuring percent vegetative cover. Soil Sci. Soc. Am. J. 43:578-582.

Willis, W. O., and M. Amemiya. 1973. Tillage management principles: Soil temperature effects. pp. 22-42. In Conservation Tillage. Proc. of a Natl. Conf., Soil Conserv. Soc. Am., Ankeny, Iowa.

SECTION II. SOIL SURFACE ROUGHNESS EFFECTS ON RADIATION REFLECTANCE AND SOIL HEAT FLUX

ABSTRACT

Soil surface roughness provides a mechanism to alter soil reflectance and the surface energy balance. A field study was conducted to determine the effect of surface roughness on energy absorption and energy partitioning at the soil surface. A range of surface roughness conditions were created by varying the intensity of secondary tillage following moldboard plowing. Parameters measured included spectral reflectance, net radiation, soil temperature and soil heat flux.

Reflectance of solar radiation decreased with increasing surface roughness. The greatest differences in reflectance among surface roughness conditions occurred between radiation wavelengths of 850 and 1350 nm. Reflectance was similar between 400 and 850 nm. Reflectance was increased about 25% after a 0.047-m rainfall event, probably because of decreased surface roughness. Net radiation increased with increased surface roughness. Soil heat flux at 0.01-m was similar for all roughness conditions. This indicates that the latent and/or sensible heat flux was increased by increasing surface roughness. Theoretical considerations indicated that increasing surface roughness resulted in greater transport of energy from the soil surface to the atmosphere.

INTRODUCTION

Soil temperature is an important factor in agriculture because of its effect on plant growth and development. Soil temperature affects seed germination, plant emergence, root growth, nutrient uptake, and plant development. The range of optimal soil temperatures for crop production is fairly small. Spring soil temperatures are usually below optimum in the corn belt (Radke, 1982). There have been many efforts to modify the temperature regime of soil, including mulching, tillage, and changing the color, shape, and orientation of the seedbed.

Soil temperatures are determined by the soil thermal properties [volumetric heat capacity (C_v) and thermal conductivity (λ)] and the soil surface heat flux (G). Both the radiant energy absorbed by the soil surface and the partitioning of net radiation (R_n) at the soil surface influence G. Radiation relationships at the soil surface are described by the surface energy balance equation:

$$R_n = (1-r)R_s + R_l - \varepsilon\sigma T_s^4 \tag{1}$$

where R_s and R_l are the incoming short wave solar radiation and incoming longwave radiation. The surface emissivity is ε, r is the short wave reflection coefficient, σ is the Stefan-Boltzmann constant, and T_s the absolute surface temperature. Net radiation may be partitioned according to the equation:

$$R_n = G + A + LE \tag{2}$$

where G, A, and LE are the soil, sensible and latent heat flux, respectively. Thus, soil temperatures are affected by changes in R_n due to differences in reflectance or emittance and by the partitioning of R_n.

Net radiation is usually increased on a rough soil surface as compared to a smooth soil surface (Cary and Evans, 1975; Allmaras et al., 1977). This is due in part to a lower reflection coefficient on a rough soil surface (Gausman et al., 1977; Cipra et al., 1971; Idso et al., 1975; Coulson and Reynolds, 1971). Arnfield (1975) suggested multiple reflections occurring between soil particles as the mechanism to explain the decrease in surface reflectance of a rough soil surface. The decrease in a_s may result in an increase in R_n. Inasmuch as R_n is also a function of emitted long wave radiation, an increase in R_n will occur if the surface temperature does not increase enough to cause an offsetting increase in emitted longwave radiation.

Several studies of the energy balance at the soil surface have been directed toward determining changes in energy partitioning as the soil dries. For a wet bare soil, evaporation occurs at the potential rate and is a large fraction of R_n on a daily basis (Priestly and Taylor, 1972). As evaporation continues, and the soil surface dries, LE is considerably reduced (Gardner and Hillel, 1962), potentially increasing the energy available for A and G. The net effect on G will depend upon R_n and (LE + A). Examples in the literature indicate that G may increase (Idso et al., 1975) or remain about the same (Fuchs and Hadas, 1972) as the soil dries.

The surface roughness may also influence the partitioning of energy at the soil surface, however, few field studies have considered the effect of surface roughness on energy partitioning. Allmaras et al., (1977) reported G was somewhat lower in a plowed soil than in a smooth, packed soil despite greater values of R_n on the plowed soil. Heat transfer to the atmosphere by turbulent convection was greater from the rougher soil surfaces than the smooth surface.

This paper reports the measured effects of surface roughness on components of the surface energy balance equation. Additionally, a theoretical discussion of the effect of surface roughness on soil heat flux density is presented.

MATERIALS AND METHODS

The site used in this study had a Webster soil (fine-loamy, mixed, mesic, Typic Haplaquoll) with a 2% east-facing slope located one mile south of Ames, Iowa. The surface configuration of 6.6 x 6.1 m areas was modified by varying the intensity of tillage. Tillage combinations included: 1) moldboard plow (plow); 2) plow-disk (disk); 3) plow-disk-disk (disk-disk); and plow-disk-disk-roll (roll). The roll treatment consisted of smoothing the surface with a hand pulled lawn roller. Tillage combinations were replicated twice with a randomized block design. Surface residue was reduced to <2% residue cover on all treatments. Surface roughness was quantified by the random roughness index (RR) of Allmaras et al., (1966). Random roughness is essentially the standard error of microrelief meter pin heights after correction for differences in elevation due to slope. Microrelief meter pin heights were recorded for a 0.89 x 0.51-m grid at 0.025-m increments in each plot.

Incoming and reflected solar radiation was measured with an ISCO model Sr spectroradiometer (Instrumentation Specialties Company, Lincoln Nebraska).[1] The radiation sensor was attached to a 0.01-m diameter aluminum rod and extended 3-m over the soil surface to reduce shadow effects. The sensor was connected to the spectroradiometer by a fiber

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[1]Trade and company names are included for the benefit of the reader and do not imply endorsement or preferential treatment of the product by Iowa State University.

optic cable. The radiation sensor was 0.71-m above the soil surface with a field of view such that >95% of the reflected radiation sensed was reflected from within the tillage area. The spectroradiometer scanned continuously over the 400 to 1350 nm wavelength range. The millivolt output from the spectroradiometer was recorded on a strip chart recorder and transcribed manually at 50 nm intervals from 400 to 750 nm and at 100 nm intervals from 750 to 1350 nm. Both incoming and reflected radiation were measured for each plot. Reflectance was calculated as the ratio of reflected to incoming radiation.

Because only one spectroradiometer was available, reflectance determinations were made in a random rotation of the tillage sites. A complete set of measurements could be completed within a 25 minute timespan. Reflectance determinations were made under clear sky conditions. Solar zenith angles varied from 30 to 27^{o} during the time period for which spectral radiation data are presented (List, 1953).

Net radiation was measured throughout selected days with Thornwaite miniature net radiometers (C. W. Thornwaite Associates, Elmer, New Jersey).[1] The millivolt outputs from the net radiometers were recorded by an automatic data logger (CR-21, Cambell Scientific, Inc., Logan, Utah)[1] which scanned every five minutes and recorded the average net radiation over a 30 minute timespan. Total incoming solar radiation was measured with a Li-Cor LI-2005 Pyranometer (Lambda Instruments, Lincoln, Nebraska)[1] and recorded in the same manner as the net radiation.

Soil temperature was measured at three locations randomly chosen within each tillage combination area. At each location, the soil temperature at 0.01-, 0.05-, and 0.15-m depths below the soil surface was measured with copper-constantan thermocouples and recorded hourly by automatic data logging equipment (CR-5, Cambell Scientific, Inc., Logan, Utah).[1]

Soil heat flux was determined by methods described by Horton and Wierenga (1983). This method uses a harmonic solution to the heat conduction equation and allows one to calculate the apparent soil thermal diffusivity as well as soil heat flux. Soil heat flux (G) is calculated by:

$$G(z,t) = \sum_{n=1}^{m} [A_{on} C_v \sqrt{n\omega\alpha} \;\; \exp(-z\sqrt{n\omega/2\alpha}) \\ \sin\,(n\omega t + \phi_{on} + \pi/4 - z\sqrt{n\omega/2\alpha})] \tag{3}$$

where A_{on} and ϕ_{on} are the amplitude and phase angle, respectively, of the nth harmonic for the upper boundary soil temperature, ω is the radial frequency, z the depth, α the apparent thermal diffusivity, t the time, and C_v the volumetric heat capacity. The apparent thermal diffusivity was calculated for the 0.01- to 0.15-m soil increment.

Volumetric heat capacity was determined by the de Vries method (1963):

$$C_v = 1.92\ X_m + 2.51\ X_o + 4.18\ X_w \quad (MJ/m^3K) \tag{4}$$

where X_m, X_o, and X_w are the volume fractions of minerals, organic matter and water, respectively. Soil bulk density was determined from 0.076 x 0.076-m undisturbed cores. Soil water content was determined by gravimetric determination of weight loss when samples of soil were dried at 105°C for 24 h. Soil water contents are expressed on a volumetric basis. Soil moisture samples were obtained in soil depth increments of 0.0- to 0.01-, 0.01- to 0.05-, and 0.05- to 0.15-m each time reflectance measurements were made. Soil organic matter content, determined by the modified Walkley-Black method, averaged 5.3% in the surface 15 cm (Allison, 1965).

Rainfall was measured with a recording rain gauge located about 10 m from the plots.

RESULTS

Surface random roughness after tillage ranged from 4.1 cm on the plow site to 1.1 cm on the roll site (Table 1). Soil water content in the 0.0- to 0.01-m depth increment varied between 0.04 to 0.05 m^3/m^3. A high intensity rainfall event occurred 28 July, 1983 with 4.7 cm of rain received in <0.5 h. Surface random roughness measured 5 d later was decreased on all sites (Table 1). The random roughness ranged between 3.1 cm on the plow site to 0.9 cm on the roll site after the rainfall. The greatest change occurred on the disk-disk site where random roughness decreased from 3.0 cm to 1.0 cm, which was nearly the same as the roughness of the roll site. In general, the rainfall consolidated the soil surface, creating a surface seal and removing small interstitial roughness. Soil water content ranged from 0.14 to 0.15 m^3/m^3 in the 0.0- to 0.01-m depth increment 5 d after the rainfall.

The spectral reflectance of the different soil surfaces is presented in Figures 1 and 2. All reflectance curves have the concave shape characteristic of high organic matter soils (Stoner and Baumgardner, 1981). In comparing soil surface roughness effects on spectral reflectance after tillage (Fig. 1), reflectance was similar in two general wavelength ranges: 400 to 850 nm and 850 to 1350 nm. Differences in reflectance were small in the 400 to 850 nm range for all sites except for the roll site where reflectance was slightly greater. A divergence in reflectance among soil surfaces occurred in the 850 to 1350 nm wavelength range where reflectance decreased as the surface random roughness increased.

Table 1. Tilled soil surface conditions before and after 4.7 cm rainfall

Treatment	Random roughness (cm)		Soil water content (m^3/m^3)[a]	
	7/26	8/2	7/26	8/2
Plow	4.1	3.1	0.035	0.137
Disk	3.1	2.4	0.044	0.142
Disk-disk	3.0	1.0	0.049	0.145
Roll	1.1	0.9	0.046	0.143

[a] 0.0 to 0.01 m.

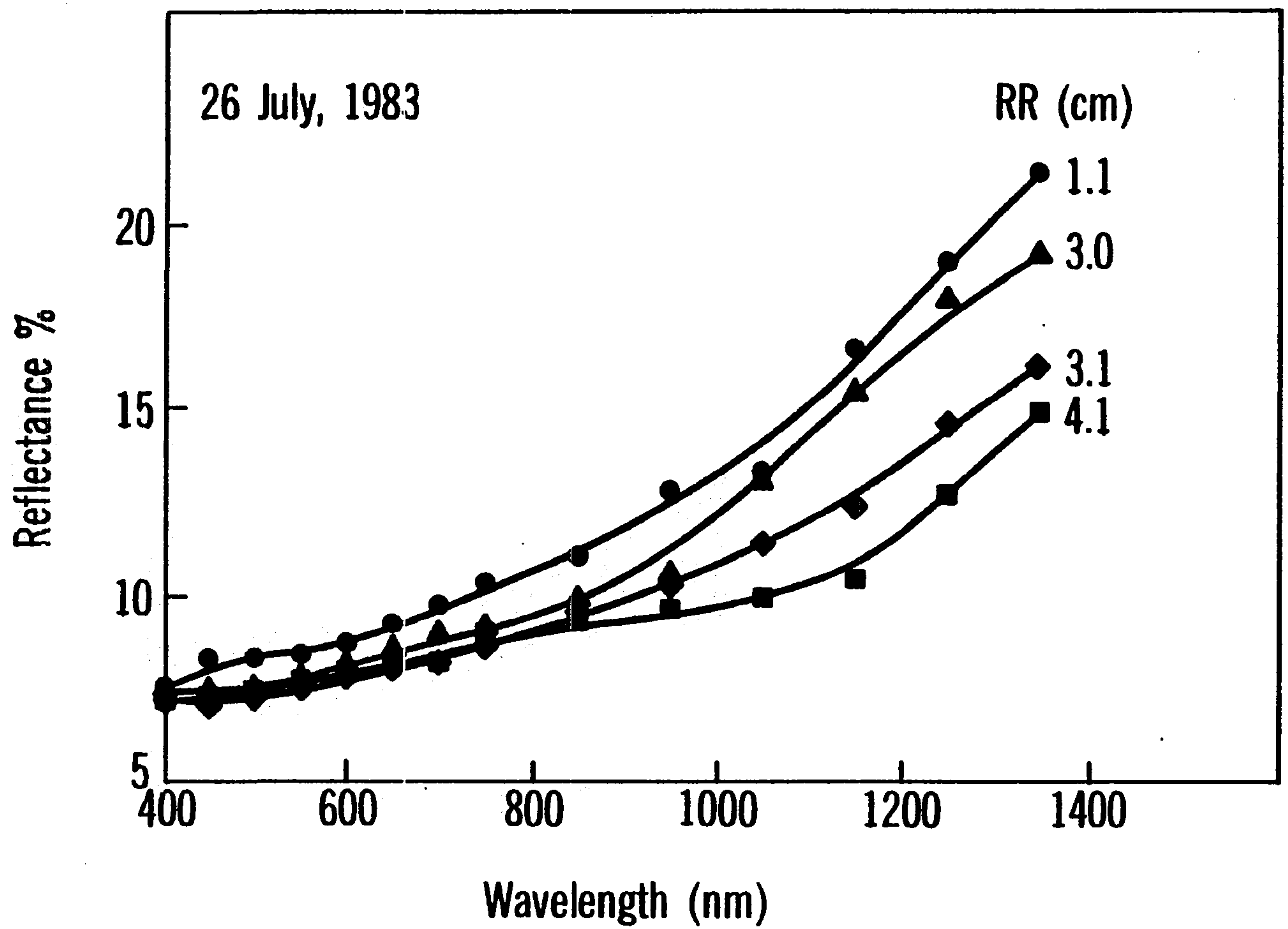


Figure 1. Spectral reflectance of soil with varying surface random roughness (RR)

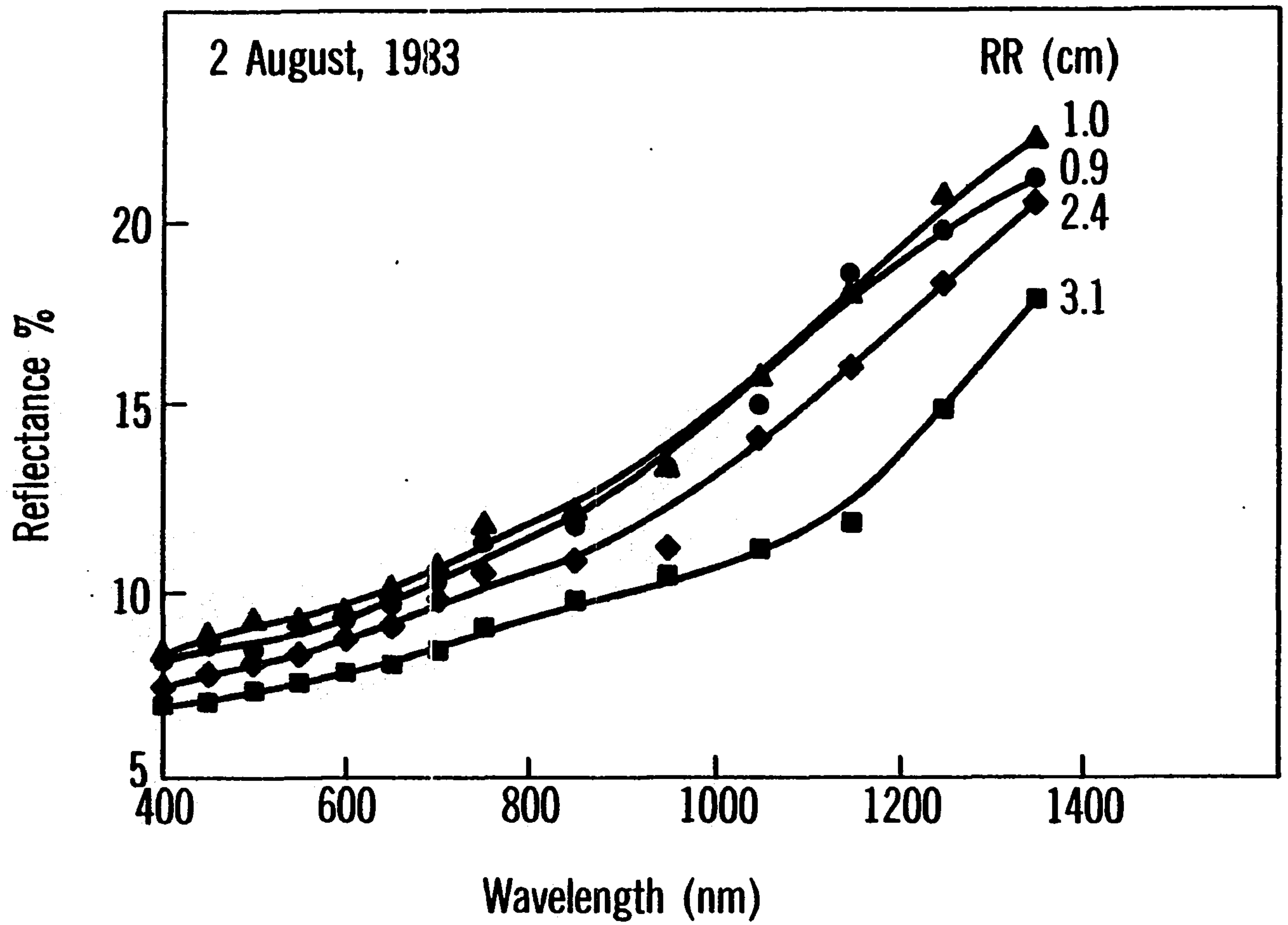
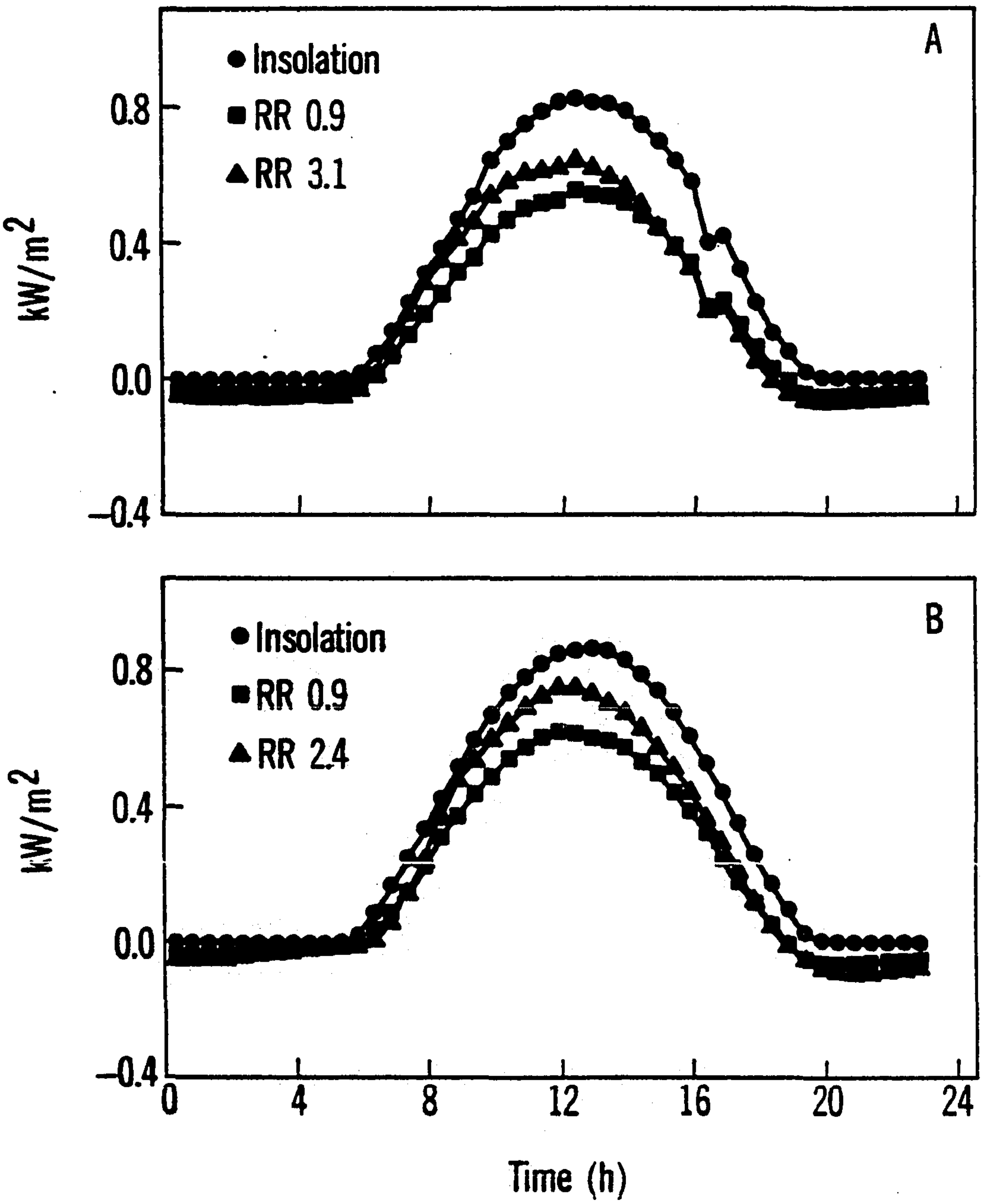


Figure 2. Spectral reflectance of soil with varying surface random roughness after 4.7 cm rainfall.

Differences in reflectance between sites also occurred after a 4.7 cm rainfall (Fig 2). Reflectance increased with increasing surface roughness in the 400 to 850 nm range. Again, however, the difference in reflection between sites was greatest in the 850 to 1350 nm range. Reflectance was consistent with the rainfall induced change in surface roughness as reflectance from the disk-disk site was similar to that of the roll site which had a similar roughness. Reflectance increased about 25% after the rainfall despite the increase in the 0.0- to 0.01-m water content from <0.05 m^3/m^3 to >0.13 m^3/m^3. As a general rule, reflectance decreases with increased water content (Bowers and Hanks, 1965). However, the reflectance measurements were made after the soil surface was visibly dry, i.e., the color change associated with large differences in reflectance (Idso et al., 1975) had already occurred. The difference in reflection probably resulted from the decrease in surface roughness and the loss of small interstitial pores between aggregates resulting in less trapping of radiation (Coulson and Reynolds, 1971).

The effect of soil surface roughness on diurnal net radiation is presented in Figure 3. Data from different days are presented in Fig. 3A and Fig. 3B, but note that the roughness of the smoother surface for each of the two days is equal. Net radiation increased as random roughness increased. Net radiation summed over 24 h was increased 11.9% and 7.1% between surfaces with a random roughness of 3.1 vs. 0.9-cm, and 2.4 vs. 0.9-cm, respectively. The greatest difference in net radiation between surfaces occurred near the time of maximum incoming solar

Figure 3. Incoming solar radiation (insolation) and net radiation (R_n) for a soil with varying surface roughness

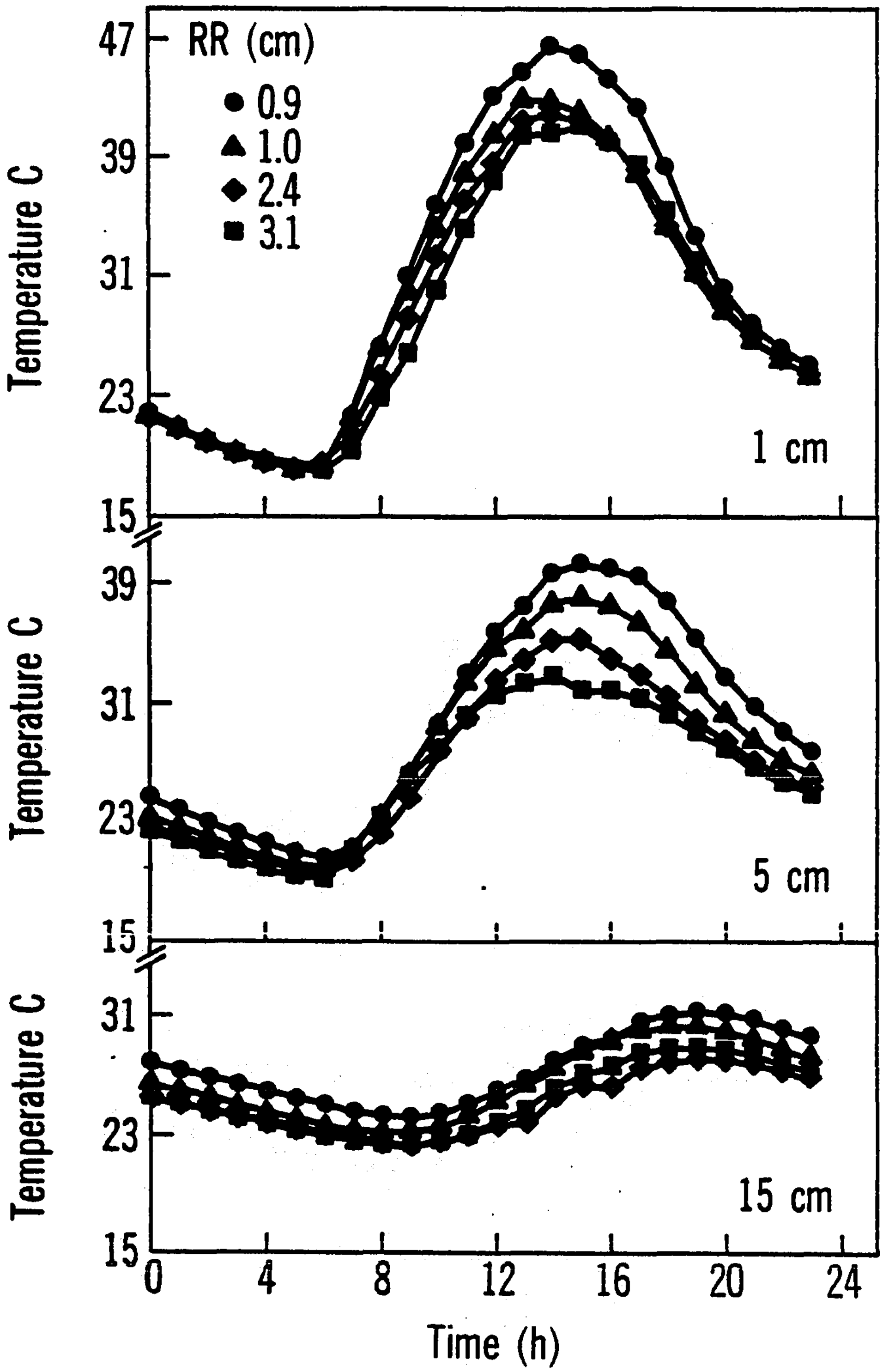

A
Insolation
RR 0.9
RR 3.1
kW/m2
0.8
0.4
0.0
–0.4
B
Insolation
RR 0.9
RR 2.4
kW/m2
0.8
0.4
0.0
–0.4
0
4
8
12
16
20
24
Time (h)

radiation.

Soil temperatures measured at three depths on 2 August, 1983 are presented in Figure 4. Near surface (1-cm) temperatures were similar during the night but diverged soon after sunrise. The maximum 1-cm soil temperature occurred in the smoothest (roll) site. Maximum 1-cm temperatures decreased as surface roughness increased. Soil temperatures at the 0.05- and 0.15-m depths were usually highest on the rolled soil surface and decreased with increasing surface roughness. Average daily soil temperatures at the 0.15-m depth were 25.6, 25.4, 26.8, and 27.9 C for the plow, disk, disk-disk, and roll sites, respectively.

Soil heat flux density calculated for the 1-cm depth is presented in Figure 5. There was little consistent difference among sites except for the roll site which had a greater heat flux amplitude than the other sites. Differences in heat flux density could result from differences in soil thermal diffusivity and volumetric heat capacity resulting from different bulk density or soil water content. Volumetric heat capacity (C_v) for the 0.01- to 0.15-m depth increments were 2.00, 2.19, 2.05, and 2.56 MJ/m^3K for the plow, disk, disk-disk, and roll sites, respectively. Corresponding values of apparent thermal diffusivity (α) were 5.24, 3.87, 5.06, and 3.98 x 10^{-7} m^2/s. Variations in C_v and α were a result of different bulk densities and volumetric water contents among tillage combinations. Bulk density increased with tillage in the order, plow < disk < disk-disk < roll. Volumetric water contents for the 0.01- to 0.15-cm depths were 0.27 m^3/m^3 in the plow and disk-disk sites, 0.32 and 0.37 m^3/m^3 in the disk and roll sites, respectively.

Figure 4. Soil temperature at 0.01-, 0.05-, 0.15-m depths for a soil with varying surface roughness



Temperature C
47
39
31
23
15
RR (cm)
0.9
1.0
2.4
3.1
1 cm
Temperature C
39
31
23
15
5 cm
Temperature C
31
23
15
15 cm
0
4
8
12
16
20
24
Time (h)

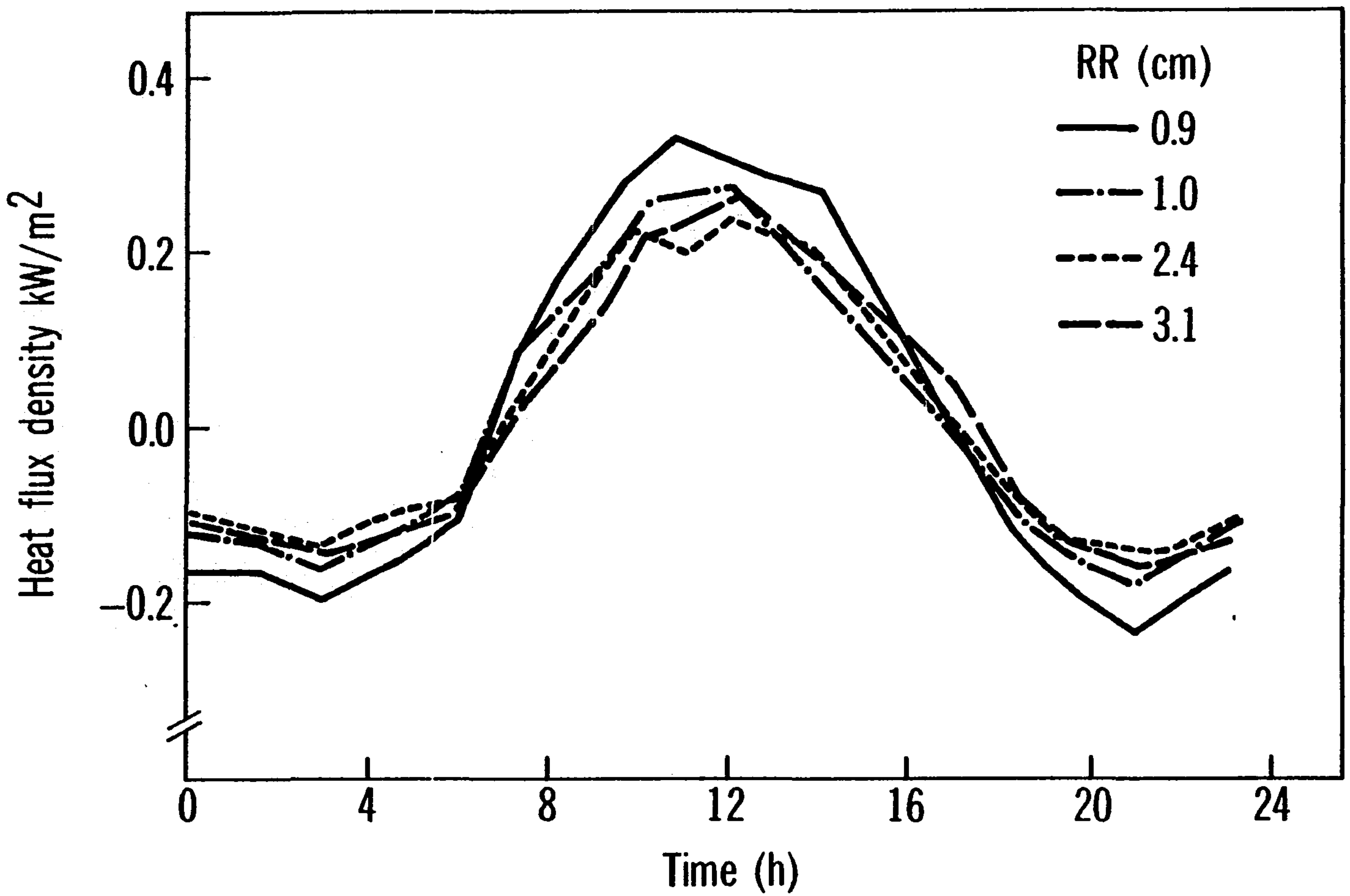


Figure 5. Soil heat flux density at the 0.01-m depth for different surface roughness conditions

DISCUSSION

Past analyses of tillage effects on soil temperature have generally ignored the effects of surface roughness. These measurements, however, show that surface roughness can affect both the net radiation and the partitioning of energy at the soil surface. As surface roughness increased, surface reflectance decreased, resulting in greater net radiation values. This indicates that more radiant energy is available to be partitioned on a rough soil surface than on a smoother surface. This process was predicted in the computer simulations by Linden (1979). If energy partitioning to latent and sensible heat fluxes remained constant, then the soil heat flux would be expected to increase. This did not occur. The observed soil heat flux was greatest on the rolled surface and about equal for the three other roughness conditions. The increase in soil heat flux on the rolled surface may have resulted from an increase in surface bulk density resulting from the smoothing method used. In general, however, these data indicate that a rougher soil surface results in a greater energy partitioning to a sensible and/or latent heat flux rather than a greater soil heat flux.

Theoretical Analysis

The apparent paradox of increased net radiation and lower soil temperatures with a roughened soil surface as compared to a smooth soil surface also has been reported by others (Cary and Evans, 1975; Allmaras et al., 1977). A possible explanation of this is the effect of surface roughness on the aerodynamic roughness length and the resulting partitioning of energy at the soil surface.

The surface energy balance equation (2) can be rewritten such that:

$$G = R_n - (LE + A) \tag{5}$$

where (LE + A), R_n, and, thus, G are dependent on the aerodynamic surface roughness length, z_o (mm). By assuming a logarithmic-wind profile, (LE + A) may be theoretically related to z_o. The following proportionality holds (Van Bavel and Hillel, 1976)

$$(LE + A) \propto [\ell n\ (2000/z_o)]^{-2} \tag{6}$$

The proportionality expressed in Eq. (6) can describe the mathematical relationship between (LE + A) and z_o by fixing all other relevant physical parameters constant (e.g., windspeed, surface and air temperature, and humidity). Table 2 shows relative values of (LE + A) for values of z_o between 1 and 10 mm.

The following equation approximates the theoretical relationship between (LE + A) and z_o over the range $1<z_o<10$ mm ($r^2 = 0.95$):

$$(LE + A)_{z_o} = (0.87 + 0.13\ z_o)\ [(LE + A)_{1mm}] \tag{7}$$

where $(LE + A)_{z_o}$ is the combined latent and sensible heat flux for a given z_o and $(LE + A)_{1mm}$ is the combined latent and sensible heat flux for a smooth surface (z_o = 1 mm). Based upon Eqs. (5) and (7), theory can be developed to describe how R_n will change with a given change in z_o in order to maintain a constant G over the range $1<z_o<10$ mm. The change in R_n, ΔR_n, is dependent on the value of R_n on a smooth soil (z_o = 1 mm) and on the ratio of $[(LE + A)_{1mm}]$ to net radiation on the smooth soil $[(R_n)_{1mm}]$.

In order to maintain a constant G, any change in (LE + A) must be offset by a corresponding change in R_n (ΔR_n). Therefore:

Table 2. Relative value of (LE+A) as a function of z_o

z_o (mm)	Relative (LE+A)
1	1.00
2	1.21
3	1.37
4	1.50
5	1.61
6	1.71
7	1.81
8	1.90
9	1.98
10	2.06

$$\Delta(LE + A) = \Delta R_n \tag{8}$$

For the smooth surface (z_o = 1 mm), assume the following relationship:

$$[(LE + A)_{1mm}] = b\ (R_n)_{1mm} \tag{9}$$

where b is an arbitrary constant. By definition:

$$\Delta(LE + A)_{z_o} = (LE + A)_{z_o} - (LE + A)_{1mm} \tag{10a}$$

and

$$\Delta R_n = (R_n)_{z_o} - (R_n)_{1mm} \tag{10b}$$

Changes in $(LE+A)_{z_o}$ for a change in z_o are predicted by combining Eqs. (7) and (10a), resulting in:

$$(LE + A)_{z_o} = 0.13\ (z_o - 1)(LE + A)_{1mm} \tag{11}$$

Roughness effects on net radiation are found by combining Eqs. (9) and (10b) resulting in:

$$(\Delta R_n)_{z_o} = (R_n)_{z_o} - 1/b\ (LE + A)_{1mm} \tag{12}$$

The change in net radiation needed to maintain an equal soil heat flux is predicted by combining Eqs. (8), (11), and (12) which results in:

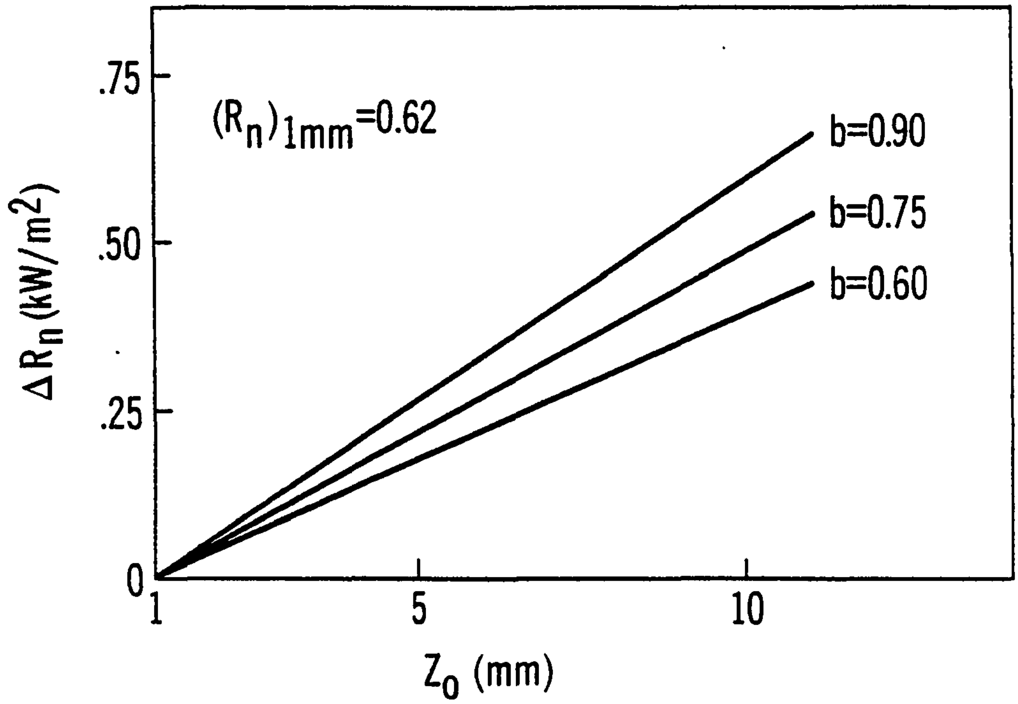
$$(R_n)_{z_o} = (LE + A)_{1mm}\ [0.13\ (z_o - 1) + 1/b] \tag{13}$$

Eq. (13) can be simplified to:

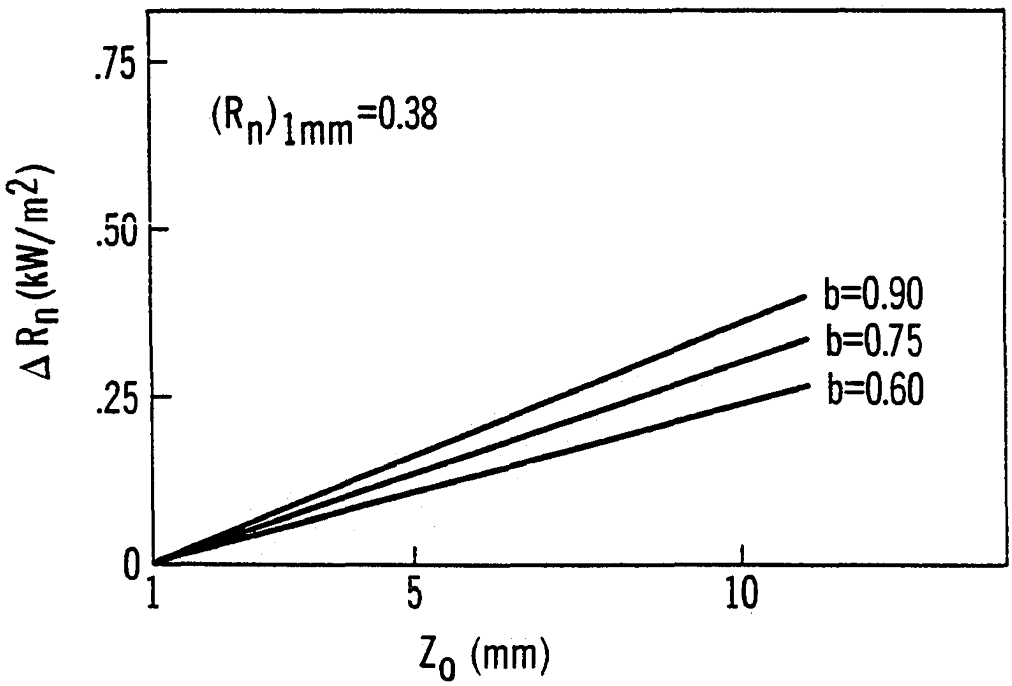
$$(\Delta R_n)_{z_o} = 0.13\ b\ (z_o - 1)\ (R_n)_{1mm} \tag{14}$$

Using Eq. (14), one can calculate the change in R_n, (ΔR_n), required to maintain a constant soil heat flux. The changes in (LE + A) associated with a change in z_o must equal ΔR_n. As seen in Eq. (14), ΔR_n for a given soil depends upon $(R_n)_{1mm}$, z_o, and b. Fig. (6) provides a graphical presentation of Eq. (14). As z_o increases, the net radiation must also increase in order to maintain a constant soil heat

Figure 6. Predicted change in R_n (ΔR_n) as a function of z_o assuming that the soil heat flux remains constant



.75
.50
.25
0
$(R_n)_{1mm}=0.62$
b=0.90
b=0.75
b=0.60
ΔR_n (kW/m^2)
1
5
10
Z_0 (mm)



.75
.50
.25
0
$(R_n)_{1mm}=0.38$
b=0.90
b=0.75
b=0.60
ΔR_n (kW/m^2)
1
5
10
Z_0 (mm)

flux. Both the net radiation of the smooth surface, $(R_n)_{1mm}$, and b affect the magnitude of the change in net radiation needed for soil heat flux to remain constant. A soil with a large $(R_n)_{1mm}$ needs a greater change in R_n to maintain a constant heat flux than a soil with a lower $(R_n)_{1mm}$. The constant (b) affects ΔR_n in the same manner as the $(R_n)_{1mm}$ in that an increase in b also results in an increase in ΔR_n.

An assumption made in the development of Eq. (14) was that soil heat flux density (G) was equal for all roughness conditions. This is not necessarily true. If, in reality, for a given change in z_o we find that $\Delta R_n < \Delta(LE + A)$, then G will decrease. The simulation results of Hammel et al., (1981) and field observations by Allmaras et al., (1977) show that this situation occurs. Alternatively, if $\Delta R_n > \Delta(LE + A)$, then G will increase. The influence of roughness on G will vary depending on the change in net radiation due to roughness for a specific soil. This may depend upon soil properties other than surface roughness. For example, Linden (1979) predicted roughness to be a more efficient radiation trap if reflectance from a smooth surface was already low. This implies that G would be more likely to be increased by roughening a dark colored soil than a light colored soil. These differences in soil characteristics may explain some of the conflicting reports which occur in the literature (Idso et al., 1975, Fuchs and Hadas, 1972).

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LITERATURE CITED

Allison, L. E. 1965. Organic carbon. In C. A. Black (ed.) Methods of soil analysis, part 2. Agronomy 9:1367-1376. American Society of Agronomy, Madison, Wisconsin.

Allmaras, R. R., R. E. Burwell, W. E. Larson, and R. F. Holt. 1966. Total porosity and random roughness of the interrow zone as influenced by tillage. U.S. Dept. Agric. Conserv. Res. Rep. 7. 21 p.

Allmaras, R. E., E. A. Hallauer, W. W. Nelson, and S. D. Evans. 1977. Surface energy balance and soil thermal property modifications by tillage-induced soil structure. Minnesota Agric. Exp. Stn. Tech. Bull. 306. 41 p.

Arnfield, A. J. 1975. A note on the diurnal, latitudinal and seasonal variation of the surface reflection coefficient. J. App. Meteorol. 14:1603-1608.

Bowers, S. A. and R. J. Hanks. 1965. Reflection of radiant energy from soils. Soil Sci. 100:130-138.

Cary, J. W. and D. D. Evans. 1975. Soil crusts. Univ. of Arizona Agric. Exp. Stn. Tech. Bull. 214.

Cipra, J. E., M. F. Baumgardner, E. R. Stoner, and R. B. MacDonald. 1971. Measuring radiance characteristics of soil with a field spectroradiometer. Soil Sci. Soc. Am. Proc. 35:1014-1017.

Coulson, K. L. and D. W. Reynolds. 1971. The spectral reflectance of natural surfaces. J. Appl. Meteorol. 10:1285-1295.

de Vries, D. A. 1963. Thermal properties in soil. Chapter 7. In W. R. Van Wijk (ed.). Physics of the Plant Environment. North Holland Publ. Co., Amsterdam.

Fuchs, M. and A. Hadas. 1972. The heat flux density in a non-homogeneous bare loessial soil. Boundary-Layer Meteorol. 3:191-200.

Gardner, W. R. and D. I. Hillel. 1962. The relation of external evaporation conditions to the drying of soils. J. Geophys. Res. 67:4319-4325.

Gausman, H. W., R. W. Learner, J. R. Noriega, R. R. Rodriguez, and C. L. Wiegand. 1977 Field-measured spectroradiometer reflectance of disked and nondisked soil with and without wheat straw. Soil Sci. Soc. Am. J. 41:793-796.

Hammel, J. E., R. I. Papendick, and G. S. Campbell. 1981. Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. Soil Sci. Soc. Am. J. 45:1016-1022.

Horton, R. and P. J. Wierenga. 1983. Estimating the soil heat flux from observations of soil temperature near the surface. Soil Sci. Soc. Am. J. 47:14-20.

Idso, S. B., R. D. Jackson, R. J. Reginato, B. A. Kimball and F. S. Nakayama. 1975. The dependence of bare soil albedo on soil water content. J. Appl. Meteorol. 14:109-113.

Linden, D. R. 1979. A model to predict soil water storage as affected by tillage practices. Ph.D. Thesis. Univ. of Minnesota. St. Paul, MN. (Diss. Abstr. 80-11844).

List, R. J. 1953. Smithsonian Meterological Tables, 6th Rev. Ed. Smithsonian Misc. Coll. 114. 527 p.

Priestly, C. H. B. and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81-92.

Radke, J. K. 1982. Managing early season soil temperatures in the northern Corn Belt using configured soil surfaces and mulches. Soil Sci. Soc. Am. J. 46:1067-1071.

Stoner, E. R., and M. F. Baumgardner. 1981. Characteristic variations in reflectance of surface soils. Soil Sci. Soc. Am. J. 45:1161-1165.

Van Bavel, C. H. M., and D. I. Hillel. 1976. Calculating potential and actual evaporation from a bare soil surface by simulation of concurrent flow of water and heat. Agric. Meteorol. 17:453-476.

GENERAL SUMMARY AND DISCUSSION

Tillage options available to the farmer are increasing and larger numbers of farmers are choosing to not moldboard plow. Fifty percent or more of the cropped land in Iowa is currently in some form of tillage which leaves 30% or more of the surface covered with crop residue (Conservation Tillage Information Center, 1984). There is an increasing need to understand mechanisms affecting physical processes occurring in the soil and especially at the soil surface which has a large influence on many physical processes occurring in the soil.

The results of two separate studies are reported in this dissertation. The first study dealt with tillage effects on soil thermal properties. The second study examined the effect of soil surface roughness on solar radiation reflectance and energy partitioning at the soil surface.

Soil thermal properties were examined in three management systems at three locations in Iowa. The management systems examined included conventional, chisel plow, and no-till. At one location, the no-till was a ridge-till system. Data were collected for two years at this site. Data were collected for one year at the other two sites where the no-till was a slot-plant system (not ridged). Soil volumetric heat capacity was similar among tillage systems. The ridged no-till tended to have a lower soil volumetric heat capacity than the conventional and chisel plow systems. The apparent thermal diffusivity as measured by harmonic analysis of soil temperature data, was significantly larger in the no-till soil than in the conventionally tilled and chisel plowed soil. The apparent thermal diffusivity was larger on the average in the conventional till system than in the chisel plow system but the difference was not statistically different. As the thermal diffusivity is defined as the ratio of thermal conductivity to the volumetric heat capacity, this implies that the thermal conductivity was altered by tillage to a much greater extent than the soil volumetric heat capacity. Independent determinations of thermal conductivity by the line source heat-probe method in the conventional tillage and no-till systems showed that thermal conductivity was at least 20% greater in the no-till than in the plowed soil.

Measurements of soil temperature were made for all tillage systems and soil heat flux was calculated. The chisel plowed soil was cooler and had a lower heat flux amplitude than the conventionally tilled soil at all sites. The no-till soil was either warmer or cooler than the conventionally tilled soil depending on whether the soil was ridged or not. The combination of ridging and the fact that residue was concentrated between the ridges in the interrow increased soil heat flux and soil temperatures in the row above that occurring in the conventional tillage system. Where the no-till was not a ridge-till system, soil temperature and heat flux were reduced compared to the conventional and chisel plow systems.

Solar radiation reflectance, net radiation, and soil heat flux were measured over a range of soil surface roughness conditions. Surface reflectance decreased and net radiation was increased with an increase in surface roughness. This indicates that more energy was available for partitioning on a rough surface than on a smooth surface. If energy partitioned to latent and sensible heat fluxes remained constant, then soil heat flux would be expected to increase on the rougher soil surfaces. However, the observed soil heat flux was greatest on the rolled surface and about equal for the other surface roughness conditions. This implies that the rougher soil surface results in a greater partitioning of net radiation into latent and/or sensible heat fluxes. This could be explained by surface roughness effects on the aerodynamic roughness length. Theoretical considerations indicated that as the roughness length increased, the amount of energy partitioned into latent and sensible heat flux also increased. This implies that net radiation must also increase on a rough surface in order to maintain a constant soil heat flux. If the increase in net radiation is less than the increase in latent and sensible heat flux, then the soil heat flux will decrease on the rougher soil surfaces.

ADDITIONAL LITERATURE CITED

Allmaras, R. R. 1967. Soil water storage as affected by infiltration and evaporation in relation to tillage-induced soil structures. pp. 37-43. In Tillage for Greater Crop Production. Am. Soc. Agric. Eng., St. Joseph, Mich.

Allmaras, R. R., W. W. Nelson, and E. A. Hallauer. 1972. Fall versus spring plowing and related heat balance in the western Corn Belt. Tech. Bulletin 283, Minn. Agr. Exp. St., St. Paul. 22 pp.

Allmaras, R. R., E. A. Hallauer, W. W. Nelson, and S. D. Evans. 1977. Surface energy balance and soil thermal property modifications by tillage induced soil structure. Minnesota Agric. Exp. Stn. Bull. 283. 21 p.

Angstrom, A. 1925. The albedo of various surfaces of ground. Geografiska Annaler, 7:323-342.

Arnfield, A. J. 1975. A note on the diurnal, latitudinal and seasonal variation of the surface reflection coefficient. J. Appl. Meteorol. 14:1603-1608.

Asrar, G. and E. T. Kanemasu. 1983. Estimating thermal diffusivity near the soil surface using Laplace transform: uniform initial conditions. Soil Sci. Soc. Am. J. 47:397-401.

Baumgardner, M. F., S. J. Kristof, C. J. Johannsen, and A. L. Zachary. 1970. Effects of organic matter on the multispectral properties of soil. Proc. Indiana Acad. Sci. 79:413-422.

Bowers, S. A., and R. J. Hanks. 1965. Reflection of radiant energy from soils. Soil Sci. 100:130-138.

Bowers, S. A., and S. J. Smith. 1972. Spectrophotometric determination of soil water content. Soil Sci. Soc. Am. Proc. 36:978-980.

Carson, J. E. 1963. Analysis of soil and air temperature by Fourier techniques. J. Geophys. Res. 68:2217-2232.

Cipra, J. E., M. F. Baumgardner, E. R. Stoner, and R. B. MacDonald. 1971. Measuring radiance characteristics of soil with a field spectroradiometer. Soil Sci. Soc. Am. Proc. 35:1014-1017.

Cipra, J. E., D. P. Franzmeier, M. E. Bauer and R. K. Boyd. 1980. Comparison of multispectral measurements from some nonvegetated soils using Landsat digital data and a spectroradiometer. Soil Sci. Soc. Am. J. 44:80-84.

Conservation Tillage Information Center. 1984. 1983 National Survey of Conservation Tillage Practices. Conservation Tillage Information Center, Fort Wayne, IN.

Coulson, K. L., and D. W. Reynolds. 1971. The spectral reflectance of natural surfaces. J. Appl. Meterol. 10:1285-1295.

Cruse, R. M., D. R. Linden, J. K. Radke, W. E. Larson, and K. Larntz. 1980. A model to predict tillage effects on soil temperature. Soil Sci. Soc. Am. J. 44:378-383.

de Vries, D. A. 1952. A non-stationary method for determining thermal conductivity of soil in situ. Soil Sci. 73:83-89.

de Vries, D. A. 1963. Thermal properties of soils. p. 210-235. In W. R. Van Wijk (ed.). Physics of the Plant Environment. North-Holland Publishing Co., Amsterdam.

de Vries, D. A., and A. J. Peck. 1958. On the cylindrical probe method of measuring thermal conductivity with special reference to soils. II. Analysis of moisture effects. Aust. J. Phys. 11:409-423.

Gausman, H. W., A. H. Gerbermann, C. L. Wiegand, R. W. Leamer, R. R. Rodriguez, and J. R. Noriegna. 1975. Reflectance differences between crop residues and bare soils. Soil Sci. Soc. Am. Proc. 39:752-755.

Gausman, H. W., R. R. Rodriguez, and A. J. Richardson. 1976. Infinite reflectance of dead compared with live vegetation. Agron. J. 68:295-296.

Gausman, H. W., R. W. Leamer, J. R. Noriega, R. R. Rodriguez, and C. L. Wiegand. 1977. Field-measured spectroradiometric reflectances of disked and nondisked soil with and without wheat straw. Soil Sci. Soc. Am. J. 41:793-796.

Graser, E. A., and C. H. M. Van Bavel. 1982. The effect of soil moisture upon soil albedo. Agric. Meteorol. 27:17-26.

Hadas, A. 1977. Evaluation of theoretically predicted thermal conductivities of soils under field and laboratory conditions. Soil Sci. Soc. Am. J. 41:460-466.

Hanks, R. J., D. D. Austin, and W. T. Ondrechen. 1971. Soil temperature estimation by a numerical method. Soil Sci. Soc. Am. Proc. 35:665-667.

Hay, R. K. M., J. C. Holmes, and E. A. Hunter. 1978. The effects of tillage, direct drilling and nitrogen fertilizer on soil temperature under a barley crop. J. Soil Sci. 29:174-183.

Hillel, D. 1980. Fundamentals of soil physics. Academic Press, New York.

Horton, R., and P. J. Wierenga. 1984. The effect of column wetting on soil thermal conductivity. Soil Science 138:102-108.

Horton, R., P. J. Wierenga, and D. R. Nielsen. 1983. Evaluation of methods for determining the apparent thermal diffusivity of soil near the surface. Soil Sci. Soc. Am. J. 47:25-32.

Idso, S. B., and R. J. Reginato. 1974. Assessing soil water status via albedo measurement. Hydrol. Water Res. Ariz. Southwest 4:41-55.

Idso, S. B., R. D. Jackson, R. J. Reginato, B. A. Kimball, and F. S. Nakayama. 1975. The dependence of bare soil albedo on soil water content. J. Appl. Meteorol. 14:109-113.

Jackson, R. D. and Don Kirkham. 1958. Method of measurement of the real thermal diffusivity of moist soil. Soil Sci. Soc. Am. Proc. 22:479-482.

Karmonov, I. I. 1970. Study of soils from the spectral composition of reflected radiation. Sov. Soil Sci. 4:226-238.

Kimball, B. A., and R. D. Jackson. 1975. Soil heat flux determination: A null alignment method. Agric. Meteorol. 15:1-9.

Kimball, B. A., R. D. Jackson, F. S. Nakayama, S. B. Idso, and R. J. Reginato. 1976. Soil heat flux determination: temperature gradient method with computed thermal conductivities. Soil Sci. Soc. Am. Proc. 40:25-28.

Lindberg, J. D., and D. G. Snyder. 1972. Diffuse reflectance spectra of several clay minerals. Am. Mineral. 57:485-493.

Linden, D. R. 1979. A model to predict soil water storage as affected by tillage practices. Ph.D. Thesis. Univ. of Minnesota, St. Paul, MN. (Diss. Abstr. Int. 80-11844).

Mathews, H. L., R. L. Cunningham, and G. W. Peterson. 1973. Spectral reflectance of selected Pennsylvania soils. Soil Sci. Soc. Am. Proc. 37:421-424.

Parikh, R. J., J. A. Havens, and H. D. Scott. 1979. Thermal diffusivity and conductivity of moist porous media. Soil Sci. Soc. Am. J. 43:1050-1052.

Peterson, J. B., R. H. Beck, and B. F. Robinson. 1979. Predictability of change in soil reflectance on wetting. Proc. Symp. Machine Processing of Remotely Sensed Data, 5th (West Lafayette, Ind.) 27-29 June. IEEE Inc., Piscataway, NJ.

Rosenberg, N. J., B. L. Blad, and S. B. Verma. 1983. Microclimate: The Biological Environment. Second edition. John Wiley & Sons, New York.

Sepaskhah, A. R., and L. Boersma. 1979. Thermal conductivity of soils as a function of temperature and water content. Soil Sci. Soc. Am. J. 43:439-444.

Shields, J. A., E. A. Paul, R. J. St. Arnaud, and W. K. Head. 1968. Spectrophotometric measurement of soil color, and its relationship to moisture and organic matter. Can. J. Soil Sci. 48:271-280.

Skaggs, R. W., and E. M. Smith. 1967. Apparent thermal conductivity of soil as related to soil porosity. Paper No. 67-114 presented at the Annual Meeting of the ASAE at Saskatoon, Saskatchewan, June 27-30.

Stoner, E. R., and M. F. Baumgardner. 1981. Characteristic variations in reflectance of surface soils. Soil Sci. Soc. Am. J. 45:1161-1165.

Stoner, E. R., M. F. Baumgardner, R. A. Weismiller, L. L. Biehl, and B. F. Robinson. 1980. Extension of laboratory measured soil spectra to field conditions. Soil Sci. Soc. Am. J. 44:572-574.

Thompson, D. R., D. E. Pitts, and K. E. Henderson. 1983. Simulation of landsat multispectral scanner response of soils using laboratory reflectance measurements. Soil Sci. Soc. Am. J. 47:542-546.

Van Doren, D. M., Jr., and R. R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. p. 49-83. In W. R. Oschwald (ed.). Crop residue management systems. Am. Soc. Agron. Spec. Publ. 31.

van Duin, R. H. A. 1956. On the influence of tillage on conduction of heat, diffusion of air and infiltration of water in soil. Versl. Landbouwkd. Onderz. No. 62.7:82.

van Wijk, W. R. 1966. Physics of the plant environment. Second edition. John Wiley & Sons, New York.

von Hoyningen-Huene, S. 1971. Einfluss einer Strohdicke auf den Strahlungshaausalt des Endbodens. (The influence of straw cover on the radiation balance of the soil.) Agric. Meteorol. 9:63-75 (English summary).

Wierenga, P. J., D. R. Nielsen, and R. M. Hagan. 1969. Thermal properties of a soil based upon field and laboratory measurements. Soil Sci Soc. Am. Proc. 33:354-360.

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APPENDIX A. SOIL TEMPERATURE VALUES FOR SELECTED DATES IN THREE MANAGEMENT SYSTEMS AT THREE IOWA LOCATIONS

AVERAGE SOIL TEMPERATURE DATA FROM NASHUA 6/1/83, NO-TILL TREATMENT

		DEPTH (CM)					DEPTH (CM)		
REP	HOUR	2.5	5.0	15.0	REP	HOUR	2.5	5.0	15.0
1	-3.	12.6	13.3	13.9	2	-3.	12.2	13.0	13.5
1	-2.	12.1	12.9	13.7	2	-2.	11.4	12.4	13.4
1	-1.	11.8	12.6	13.4	2	-1.	11.0	11.9	13.3
1	0.	11.4	12.3	13.1	2	0.	10.6	11.6	13.2
1	1.	11.0	11.9	12.9	2	1.	10.1	11.2	13.1
1	2.	10.7	11.6	12.7	2	2.	9.8	10.9	12.9
1	3.	10.3	11.4	12.4	2	3.	9.3	10.6	12.8
1	4.	10.1	11.1	12.2	2	4.	9.1	10.3	12.5
1	5.	9.8	10.8	11.9	2	5.	8.8	9.9	12.4
1	6.	10.2	10.9	11.7	2	6.	9.4	10.0	12.1
1	7.	11.5	11.2	11.6	2	7.	11.4	10.9	11.8
1	8.	13.3	12.0	11.5	2	8.	14.5	12.6	11.6
1	9.	15.9	13.4	11.8	2	9.	17.6	14.6	11.4
1	10.	18.6	15.1	12.0	2	10.	19.9	16.5	11.6
1	11.	21.1	16.8	12.5	2	11.	22.1	18.3	12.0
1	12.	23.0	18.5	13.3	2	12.	23.6	20.0	12.4
1	13.	22.0	18.4	14.3	2	13.	22.1	19.8	12.9
1	14.	22.1	18.6	14.9	2	14.	21.9	19.8	13.4
1	15.	20.4	18.0	15.4	2	15.	19.9	18.9	13.9
1	16.	19.1	17.0	15.7	2	16.	18.6	17.8	14.1
1	17.	18.7	16.8	15.8	2	17.	17.9	17.5	14.4
1	18.	17.0	16.1	15.9	2	18.	16.4	16.5	14.5
1	19.	16.2	15.5	15.8	2	19.	15.6	15.8	14.6
1	20.	15.6	15.2	15.7	2	20.	15.1	15.3	14.6
1	21.	15.1	14.9	15.4	2	21.	14.5	14.9	14.6
1	22.	14.4	14.5	15.3	2	22.	13.8	14.4	14.5
1	23.	14.1	14.3	15.1	2	23.	13.5	14.0	14.4
1	24.	14.1	14.1	14.8	2	24.	13.6	13.9	14.3
1	25.	14.0	14.1	14.6	2	25.	13.4	13.8	14.3
1	26.	13.8	14.0	14.4	2	26.	13.3	13.7	14.1

AVERAGE SOIL TEMPERATURE DATA FROM NASHUA 6/1/83, PLOW TREATMENT

		DEPTH (CM)					DEPTH (CM)		
REP	HOUR	2.5	5.0	15.0	REP	HOUR	2.5	5.0	15.0
1	-3.	12.5	14.1	14.9	2	-3.	12.8	13.7	14.2
1	-2.	11.7	13.2	14.7	2	-2.	11.9	12.9	14.0
1	-1.	11.0	12.4	14.4	2	-1.	11.2	12.3	13.8
1	0.	10.4	11.8	14.1	2	0.	10.6	11.8	13.5
1	1.	9.8	11.2	13.9	2	1.	10.0	11.3	13.3
1	2.	9.4	10.6	13.5	2	2.	9.5	10.8	13.1
1	3.	8.9	10.2	13.3	2	3.	9.1	10.4	12.8
1	4.	8.6	9.8	13.0	2	4.	8.8	10.0	12.5
1	5.	8.5	9.3	12.8	2	5.	8.4	9.8	12.3
1	6.	10.0	9.8	12.5	2	6.	9.3	10.0	12.1
1	7.	13.3	11.4	12.1	2	7.	11.4	11.1	11.9
1	8.	17.8	14.0	12.0	2	8.	14.6	13.1	11.8
1	9.	21.7	16.8	12.1	2	9.	17.9	15.6	11.9
1	10.	24.9	19.6	12.6	2	10.	20.8	17.9	12.4
1	11.	28.5	22.1	13.3	2	11.	23.6	20.1	13.0
1	12.	29.9	24.8	14.3	2	12.	25.9	22.4	13.8
1	13.	28.4	24.6	15.1	2	13.	25.3	22.4	14.4
1	14.	28.0	24.9	16.0	2	14.	25.3	22.8	15.3
1	15.	25.1	23.8	16.8	2	15.	23.4	22.1	15.9
1	16.	23.1	22.1	17.2	2	16.	21.7	20.7	16.3
1	17.	21.9	21.6	17.4	2	17.	21.0	20.2	16.4
1	18.	19.1	20.0	17.4	2	18.	18.8	18.8	16.4
1	19.	17.8	18.7	17.5	2	19.	17.6	17.6	16.4
1	20.	16.8	17.8	17.3	2	20.	16.6	16.8	16.3
1	21.	15.9	16.9	17.0	2	21.	15.8	16.1	16.0
1	22.	14.6	16.1	16.8	2	22.	14.6	15.4	15.8
1	23.	14.3	15.3	16.4	2	23.	14.2	14.8	15.6
1	24.	14.3	15.0	16.2	2	24.	14.0	14.5	15.4
1	25.	14.0	14.7	16.0	2	25.	13.8	14.3	15.2
1	26.	13.7	14.4	15.6	2	26.	13.5	14.1	14.9

AVERAGE SOIL TEMPERATURE DATA FROM NASHUA 6/1/83, CHISEL TREATMENT

REP	HOUR	DEPTH (CM) 2.5	5.0	15.0	REP	HOUR	DEPTH (CM) 2.5	5.0	15.0
1	-3.	12.9	13.8	14.4	2	-3.	12.0	13.0	13.6
1	-2.	12.0	12.9	14.3	2	-2.	11.3	12.3	13.5
1	-1.	11.2	12.3	13.9	2	-1.	10.8	11.8	13.4
1	0.	10.6	11.6	13.6	2	0.	10.3	11.4	13.2
1	1.	10.0	11.1	13.5	2	1.	9.8	10.9	13.0
1	2.	9.5	10.8	13.3	2	2.	9.4	10.5	12.8
1	3.	9.0	10.3	13.0	2	3.	9.0	10.1	12.6
1	4.	8.6	10.0	12.8	2	4.	8.7	9.8	12.4
1	5.	8.4	9.7	12.5	2	5.	8.5	9.6	12.2
1	6.	9.4	10.0	12.1	2	6.	9.7	10.0	12.0
1	7.	12.0	11.4	11.8	2	7.	12.3	11.3	11.8
1	8.	15.3	13.7	11.6	2	8.	16.1	13.6	11.8
1	9.	18.5	16.1	11.6	2	9.	19.4	16.0	11.9
1	10.	21.4	18.4	11.9	2	10.	21.9	18.0	12.2
1	11.	24.4	20.7	12.5	2	11.	24.8	20.0	12.8
1	12.	26.2	23.0	13.2	2	12.	25.7	22.0	13.4
1	13.	25.3	22.8	13.9	2	13.	24.6	21.8	14.0
1	14.	25.4	23.2	14.8	2	14.	24.4	22.1	14.6
1	15.	23.6	22.4	15.5	2	15.	22.4	21.3	15.2
1	16.	21.9	20.9	16.0	2	16.	20.7	19.9	15.5
1	17.	21.1	20.4	16.2	2	17.	19.8	19.4	15.7
1	18.	18.9	19.0	16.3	2	18.	17.7	18.1	15.8
1	19.	17.6	17.8	16.3	2	19.	16.6	17.0	15.7
1	20.	16.6	16.8	16.2	2	20.	15.8	16.3	15.6
1	21.	15.8	16.1	16.0	2	21.	15.0	15.7	15.4
1	22.	14.6	15.3	15.9	2	22.	14.0	14.9	15.3
1	23.	14.2	14.7	15.6	2	23.	13.8	14.4	15.1
1	24.	14.0	14.4	15.4	2	24.	13.8	14.3	14.9
1	25.	13.8	14.3	15.1	2	25.	13.6	14.1	14.8
1	26.	13.5	14.0	14.9	2	26.	13.3	13.8	14.6

AVERAGE SOIL TEMPERATURE DATA FROM SUTHERLAND 6/1/83, NO-TILL TREATMENT

REP	HOUR	DEPTH (CM) 2.5	5.0	15.0	REP	HOUR	DEPTH (CM) 2.5	5.0	15.0
1	-3.	15.3	15.2	14.8	2	-3.	15.8	16.2	15.8
1	-2.	14.6	14.6	14.6	2	-2.	14.8	15.6	15.5
1	-1.	13.8	14.0	14.2	2	-1.	13.8	15.0	15.3
1	0.	13.2	13.5	14.0	2	0.	13.0	14.3	15.0
1	1.	12.5	12.8	13.7	2	1.	12.1	13.6	14.8
1	2.	11.7	12.4	13.4	2	2.	11.3	12.9	14.4
1	3.	11.2	11.8	13.1	2	3.	10.6	12.3	14.0
1	4.	10.7	11.3	12.8	2	4.	9.9	11.7	13.7
1	5.	10.1	10.8	12.4	2	5.	9.3	11.3	13.3
1	6.	9.9	10.4	12.1	2	6.	9.1	10.8	12.9
1	7.	9.8	10.3	11.8	2	7.	9.6	10.6	12.5
1	8.	10.4	10.5	11.4	2	8.	11.0	11.1	12.3
1	9.	11.5	11.2	11.5	2	9.	12.7	11.9	12.0
1	10.	12.8	12.0	11.6	2	10.	14.8	13.0	12.0
1	11.	14.5	13.3	11.8	2	11.	17.0	13.8	12.3
1	12.	15.9	14.5	12.1	2	12.	18.7	14.8	12.7
1	13.	17.4	15.9	12.6	2	13.	20.3	15.0	13.3
1	14.	18.3	16.9	13.3	2	14.	21.2	16.3	13.8
1	15.	19.1	17.9	13.9	2	15.	21.8	16.5	14.4
1	16.	19.1	18.2	14.4	2	16.	21.6	17.4	15.0
1	17.	18.7	18.1	14.8	2	17.	20.8	17.9	15.5
1	18.	17.9	17.5	15.0	2	18.	19.6	18.1	15.8
1	19.	16.9	16.8	15.0	2	19.	18.3	17.9	16.0
1	20.	15.7	15.8	15.0	2	20.	16.6	17.3	16.1
1	21.	14.7	14.8	14.8	2	21.	15.1	16.3	16.1
1	22.	13.9	14.0	14.4	2	22.	13.9	15.6	15.9
1	23.	13.0	13.3	14.1	2	23.	12.9	14.6	15.4
1	24.	12.4	12.6	13.8	2	24.	12.0	13.9	15.1
1	25.	11.7	12.1	13.4	2	25.	11.3	13.3	14.7
1	26.	11.2	11.6	13.0	2	26.	10.8	12.7	14.3

AVERAGE SOIL TEMPERATURE DATA FROM SUTHERLAND 6/1/83, PLOW TREATMENT

		DEPTH (CM)					DEPTH (CM)		
REP	HOUR	2.5	5.0	15.0	REP	HOUR	2.5	5.0	15.0
1	-3.	16.0	15.6	15.6	2	-3.	15.8	16.2	15.1
1	-2.	15.1	14.8	15.3	2	-2.	14.6	15.5	15.0
1	-1.	14.2	14.1	15.1	2	-1.	13.7	14.8	14.7
1	0.	13.3	13.3	14.8	2	0.	12.8	14.0	14.5
1	1.	12.5	12.6	14.6	2	1.	11.9	13.4	14.3
1	2.	11.8	11.8	14.2	2	2.	11.1	12.7	14.0
1	3.	11.1	11.1	13.9	2	3.	10.3	12.0	13.7
1	4.	10.5	10.5	13.5	2	4.	9.8	11.5	13.3
1	5.	9.9	10.0	13.2	2	5.	9.2	11.0	13.0
1	6.	9.6	9.7	12.9	2	6.	8.9	10.6	12.7
1	7.	9.8	9.6	12.5	2	7.	9.1	10.3	12.3
1	8.	10.7	10.3	12.4	2	8.	10.9	10.6	12.0
1	9.	12.0	11.6	12.3	2	9.	13.1	11.5	11.8
1	10.	13.5	12.8	12.4	2	10.	15.7	12.8	11.9
1	11.	15.3	14.3	12.7	2	11.	18.4	14.4	12.0
1	12.	17.0	15.7	13.2	2	12.	20.5	15.9	12.2
1	13.	18.7	16.9	13.7	2	13.	22.4	17.5	12.9
1	14.	19.8	18.2	14.3	2	14.	23.4	18.8	13.3
1	15.	20.8	19.0	14.8	2	15.	24.1	19.6	13.9
1	16.	21.0	19.3	15.3	2	16.	23.8	20.1	14.5
1	17.	20.3	19.1	15.7	2	17.	22.7	20.0	15.0
1	18.	19.5	18.6	15.9	2	18.	20.9	19.4	15.3
1	19.	18.4	17.8	15.9	2	19.	18.9	18.5	15.5
1	20.	16.9	16.6	15.9	2	20.	16.8	17.4	15.5
1	21.	15.4	15.3	15.7	2	21.	15.0	16.3	15.5
1	22.	14.4	14.3	15.4	2	22.	13.7	15.2	15.2
1	23.	13.5	13.4	15.1	2	23.	12.7	14.3	14.9
1	24.	12.7	12.7	14.7	2	24.	11.9	13.5	14.6
1	25.	11.9	11.9	14.4	2	25.	11.0	12.8	14.2
1	26.	11.4	11.3	14.0	2	26.	10.5	12.2	13.9

AVERAGE SOIL TEMPERATURE DATA FROM SUTHERLAND 6/1/83, CHISEL TREATMENT

REP	HOUR	DEPTH (CM) 2.5	5.0	15.0	REP	HOUR	DEPTH (CM) 2.5	5.0	15.0
1	-3.	15.3	16.0	15.1	2	-3.	16.0	16.6	15.9
1	-2.	14.4	15.1	14.9	2	-2.	14.9	15.8	15.6
1	-1.	13.6	14.4	14.8	2	-1.	13.9	14.9	15.3
1	0.	12.8	13.6	14.6	2	0.	13.0	14.1	15.0
1	1.	11.9	12.8	14.3	2	1.	12.1	13.4	14.6
1	2.	11.1	12.1	14.0	2	2.	11.3	12.8	14.2
1	3.	10.4	11.5	13.8	2	3.	10.5	12.0	13.8
1	4.	9.8	10.9	13.4	2	4.	9.9	11.4	13.4
1	5.	9.3	10.3	13.1	2	5.	9.3	10.8	13.0
1	6.	9.0	9.9	12.8	2	6.	9.0	10.3	12.6
1	7.	9.3	10.0	12.4	2	7.	9.6	10.3	12.3
1	8.	10.5	10.7	12.0	2	8.	11.1	10.8	11.9
1	9.	12.2	11.9	11.7	2	9.	13.0	11.9	11.9
1	10.	14.3	13.8	11.7	2	10.	15.6	13.4	12.0
1	11.	16.6	15.8	11.8	2	11.	18.2	15.3	12.4
1	12.	18.6	17.5	12.1	2	12.	20.3	16.9	13.0
1	13.	20.3	19.3	12.6	2	13.	22.4	18.5	13.7
1	14.	21.1	20.3	13.1	2	14.	23.1	19.8	14.5
1	15.	21.7	21.0	13.7	2	15.	23.7	20.6	15.1
1	16.	21.5	21.1	14.1	2	16.	23.3	20.8	15.7
1	17.	20.6	20.6	14.4	2	17.	22.1	20.4	16.3
1	18.	19.3	19.5	14.8	2	18.	20.4	19.7	16.4
1	19.	17.8	18.3	15.0	2	19.	18.8	18.8	16.4
1	20.	16.2	16.9	15.2	2	20.	16.7	17.5	16.4
1	21.	14.7	15.6	15.2	2	21.	14.9	16.2	16.1
1	22.	13.6	14.4	15.1	2	22.	13.8	15.1	15.7
1	23.	12.6	13.5	14.8	2	23.	12.7	14.1	15.3
1	24.	11.8	12.8	14.5	2	24.	11.8	13.3	14.8
1	25.	11.1	12.0	14.1	2	25.	11.1	12.6	14.3
1	26.	10.4	11.3	13.8	2	26.	10.3	11.9	13.9

AVERAGE SOIL TEMPERATURE DATA FROM AMES 5/23/83, NO-TILL TREATMENT

REP	HOUR	DEPTH (CM) 2.5	5.0	15.0	REP	HOUR	DEPTH (CM) 2.5	5.0	15.0
1	21.	12.8	13.4	19.1	2	21.	11.7	13.2	18.0
1	22.	11.7	12.4	18.2	2	22.	10.9	12.5	17.1
1	23.	10.8	11.5	17.2	2	23.	10.3	11.8	16.3
1	0.	10.0	10.9	16.3	2	0.	9.8	11.2	15.5
1	1.	9.3	10.3	15.6	2	1.	9.1	10.6	14.9
1	2.	8.7	9.6	15.0	2	2.	8.6	10.1	14.3
1	3.	8.2	9.1	14.3	2	3.	8.0	9.5	13.7
1	4.	7.4	8.5	13.7	2	4.	7.5	9.0	13.1
1	5.	7.0	8.1	13.0	2	5.	7.1	8.6	12.4
1	6.	7.2	8.0	12.3	2	6.	7.5	8.5	11.9
1	7.	8.6	8.9	11.8	2	7.	10.0	9.8	11.6
1	8.	11.3	10.9	11.7	2	8.	13.4	11.9	11.7
1	9.	14.5	13.1	11.9	2	9.	16.6	14.1	12.1
1	10.	18.0	15.8	12.6	2	10.	19.7	16.5	12.9
1	11.	20.6	17.7	13.5	2	11.	20.8	18.1	13.9
1	12.	23.5	20.1	14.6	2	12.	25.0	20.6	15.1
1	13.	26.1	22.1	15.7	2	13.	27.1	22.5	16.3
1	14.	27.6	23.6	16.9	2	14.	27.7	23.6	17.4
1	15.	28.2	24.5	18.1	2	15.	27.5	23.9	18.4
1	16.	28.2	24.8	19.0	2	16.	26.3	23.6	19.2
1	17.	27.0	24.3	19.8	2	17.	24.2	22.7	19.6
1	18.	24.9	23.0	20.2	2	18.	21.7	21.3	19.7
1	19.	22.1	21.3	20.3	2	19.	19.4	19.8	19.5
1	20.	18.9	19.1	19.9	2	20.	17.3	18.3	18.8
1	21.	16.6	17.3	19.1	2	21.	15.6	16.8	18.0
1	22.	15.2	15.9	18.2	2	22.	14.4	15.8	17.1
1	23.	14.1	14.8	17.2	2	23.	13.5	14.9	16.3
1	0.	13.2	14.0	16.3	2	0.	12.8	14.1	15.5
1	1.	12.4	13.3	15.6	2	1.	12.1	13.4	14.9
1	2.	11.7	12.6	15.0	2	2.	11.5	12.8	14.3

AVERAGE SOIL TEMPERATURE DATA FROM AMES 5/23/83, PLOW TREATMENT

REP	HOUR	DEPTH (CM) 2.5	5.0	15.0	REP	HOUR	DEPTH (CM) 2.5	5.0	15.0
1	21.	12.3	13.4	18.3	2	21.	12.2	13.1	17.8
1	22.	11.3	12.4	17.6	2	22.	11.3	12.3	17.2
1	23.	10.4	11.6	16.7	2	23.	10.6	11.5	16.5
1	0.	9.8	11.0	16.0	2	0.	9.9	10.9	15.8
1	1.	9.2	10.3	15.3	2	1.	9.3	10.3	15.3
1	2.	8.6	9.8	14.7	2	2.	8.7	9.8	14.7
1	3.	8.0	9.2	14.1	2	3.	8.3	9.1	14.2
1	4.	7.5	8.6	13.5	2	4.	7.7	8.6	13.7
1	5.	7.0	8.1	12.9	2	5.	7.3	8.1	13.1
1	6.	7.2	8.0	12.3	2	6.	7.9	8.3	12.6
1	7.	8.6	8.8	11.8	2	7.	10.1	9.5	12.2
1	8.	10.8	10.3	11.6	2	8.	13.2	11.8	12.1
1	9.	13.6	12.4	11.8	2	9.	16.3	14.3	12.4
1	10.	16.3	14.8	12.2	2	10.	19.3	16.9	12.9
1	11.	19.4	17.5	12.9	2	11.	20.6	18.3	13.7
1	12.	22.0	19.8	13.8	2	12.	23.9	21.2	14.6
1	13.	24.6	22.1	14.9	2	13.	25.6	23.0	15.6
1	14.	26.0	23.8	15.9	2	14.	26.1	24.0	16.5
1	15.	26.8	24.6	17.0	2	15.	25.9	24.3	17.3
1	16.	26.8	24.9	17.9	2	16.	25.0	23.9	18.0
1	17.	25.6	24.6	18.7	2	17.	23.4	22.9	18.5
1	18.	23.7	23.3	19.1	2	18.	21.4	21.4	18.7
1	19.	21.4	21.6	19.2	2	19.	19.5	19.8	18.6
1	20.	18.6	19.5	18.9	2	20.	17.5	18.3	18.3
1	21.	16.6	17.6	18.3	2	21.	15.9	16.8	17.8
1	22.	15.2	16.3	17.6	2	22.	14.8	15.6	17.2
1	23.	14.1	15.1	16.7	2	23.	13.9	14.6	16.5
1	0.	13.3	14.3	16.0	2	0.	13.0	13.9	15.8
1	1.	12.5	13.6	15.3	2	1.	12.3	13.1	15.3
1	2.	11.8	12.8	14.7	2	2.	11.8	12.5	14.7

AVERAGE SOIL TEMPERATURE DATA FROM AMES 5/23/83, CHISEL TREATMENT

REP	HOUR	DEPTH (CM) 2.5	5.0	15.0	REP	HOUR	DEPTH (CM) 2.5	5.0	15.0
1	21.	12.1	13.5	17.9	2	21.	12.8	13.5	17.8
1	22.	11.3	12.8	17.4	2	22.	12.0	12.8	17.5
1	23.	10.7	12.0	16.9	2	23.	11.3	12.0	17.0
1	0.	10.0	11.4	16.3	2	0.	10.7	11.4	16.5
1	1.	9.5	10.9	15.7	2	1.	10.1	10.8	16.1
1	2.	8.9	10.4	15.3	2	2.	9.5	10.3	15.6
1	3.	8.5	10.0	14.8	2	3.	9.0	9.8	15.2
1	4.	8.0	9.5	14.3	2	4.	8.5	9.3	14.7
1	5.	7.6	9.1	13.8	2	5.	8.1	8.8	14.3
1	6.	7.8	8.9	13.3	2	6.	8.1	8.8	13.8
1	7.	9.4	9.4	12.9	2	7.	9.5	9.5	13.4
1	8.	12.4	10.9	12.7	2	8.	11.9	11.3	13.1
1	9.	15.6	12.9	12.7	2	9.	14.4	13.3	13.0
1	10.	18.8	15.3	12.9	2	10.	16.9	15.4	13.1
1	11.	21.7	17.8	13.5	2	11.	19.3	17.6	13.5
1	12.	23.7	19.4	14.2	2	12.	21.6	19.7	14.0
1	13.	25.8	21.1	15.0	2	13.	23.8	21.7	14.7
1	14.	26.5	22.3	15.9	2	14.	25.1	23.0	15.4
1	15.	26.4	22.9	16.7	2	15.	25.3	23.6	16.1
1	16.	25.9	22.9	17.4	2	16.	25.1	23.6	16.8
1	17.	24.3	22.3	17.9	2	17.	24.0	23.1	17.3
1	18.	22.1	21.3	18.3	2	18.	22.3	21.9	17.8
1	19.	19.8	19.8	18.4	2	19.	20.4	20.4	18.0
1	20.	17.4	18.2	18.3	2	20.	18.5	18.9	18.0
1	21.	15.7	16.8	17.9	2	21.	17.1	17.4	17.8
1	22.	14.6	15.6	17.4	2	22.	15.8	16.3	17.5
1	23.	13.8	14.9	16.9	2	23.	14.8	15.4	17.0
1	0.	13.0	14.1	16.3	2	0.	14.0	14.5	16.5
1	1.	12.4	13.5	15.7	2	1.	13.3	13.8	16.1
1	2.	11.8	13.0	15.3	2	2.	12.6	13.3	15.6

AVERAGE SOIL TEMPERATURE DATA FROM AMES 5/26/83, NO-TILL TREATMENT

REP	HOUR	DEPTH (CM)			REP	HOUR	DEPTH (CM)		
		2.5	5.0	15.0			2.5	5.0	15.0
1	21.	13.6	14.8	18.3	2	21.	12.6	14.3	17.7
1	22.	12.3	13.5	17.6	2	22.	11.7	13.4	17.0
1	23.	11.2	12.5	16.8	2	23.	10.8	12.6	16.3
1	0.	10.4	11.6	16.1	2	0.	10.2	11.9	15.7
1	1.	9.6	10.8	15.5	2	1.	9.6	11.2	15.2
1	2.	8.9	10.1	15.0	2	2.	9.0	10.7	14.7
1	3.	8.4	9.6	14.5	2	3.	8.5	10.2	14.2
1	4.	7.9	9.0	13.8	2	4.	8.1	14.7	13.6
1	5.	7.5	8.6	13.1	2	5.	7.7	9.3	12.9
1	6.	8.1	8.6	12.4	2	6.	8.4	9.3	12.3
1	7.	10.1	9.8	12.0	2	7.	11.2	10.9	12.0
1	8.	12.4	11.4	12.0	2	8.	13.8	12.6	12.1
1	9.	15.3	13.6	12.4	2	9.	16.9	14.6	12.7
1	10.	19.1	16.6	13.2	2	10.	21.1	17.4	13.7
1	11.	22.8	19.8	14.4	2	11.	24.5	20.1	15.0
1	12.	25.5	22.4	15.6	2	12.	26.0	22.0	16.2
1	13.	26.6	23.9	16.7	2	13.	26.3	22.9	17.3
1	14.	22.4	22.1	17.7	2	14.	21.7	21.1	18.1
1	15.	26.1	23.7	18.5	2	15.	24.6	21.9	18.6
1	16.	26.7	24.6	19.1	2	16.	24.5	22.3	19.0
1	17.	24.1	23.3	19.5	2	17.	22.1	21.2	19.1
1	18.	22.1	22.2	19.6	2	18.	20.1	20.2	19.0
1	19.	19.3	19.9	19.5	2	19.	18.4	18.8	18.8
1	20.	17.6	18.4	19.0	2	20.	17.1	17.7	18.3
1	21.	16.6	17.3	18.3	2	21.	16.2	16.9	17.7
1	22.	15.8	16.4	17.6	2	22.	15.6	16.2	17.0
1	23.	14.9	15.7	16.8	2	23.	14.9	15.6	16.3
1	0.	14.6	15.2	16.1	2	0.	14.6	15.2	15.7
1	1.	14.3	14.8	15.5	2	1.	14.2	14.9	15.2
1	2.	13.8	14.3	15.0	2	2.	13.8	14.5	14.7

AVERAGE SOIL TEMPERATURE DATA FROM AMES 5/26/83, PLOW TREATMENT

		DEPTH (CM)					DEPTH (CM)		
REP	HOUR	2.5	5.0	15.0	REP	HOUR	2.5	5.0	15.0
1	21.	13.9	15.2	18.3	2	21.	13.4	14.3	17.6
1	22.	12.7	13.9	17.6	2	22.	12.3	13.4	17.1
1	23.	11.7	12.9	17.0	2	23.	11.4	12.4	16.7
1	0.	10.8	12.1	16.4	2	0.	10.6	11.6	16.2
1	1.	10.1	11.4	15.9	2	1.	9.9	10.9	15.8
1	2.	9.4	10.6	15.4	2	2.	9.3	10.3	15.4
1	3.	8.8	10.1	14.9	2	3.	8.8	9.8	15.0
1	4.	8.2	9.6	14.3	2	4.	8.3	9.3	14.5
1	5.	7.7	9.0	13.6	2	5.	7.9	8.9	14.0
1	6.	8.2	8.9	13.0	2	6.	9.0	9.2	13.4
1	7.	9.7	9.8	12.5	2	7.	11.5	10.7	13.1
1	8.	11.8	11.3	12.3	2	8.	14.0	12.5	12.9
1	9.	14.3	13.2	12.5	2	9.	17.1	14.7	13.1
1	10.	17.8	15.9	13.1	2	10.	20.7	17.8	13.7
1	11.	21.6	19.2	13.9	2	11.	23.5	20.4	14.4
1	12.	24.2	21.7	14.9	2	12.	25.3	22.5	15.3
1	13.	25.8	23.2	16.0	2	13.	25.6	23.2	16.1
1	14.	21.7	21.6	16.9	2	14.	21.4	21.2	16.8
1	15.	26.0	23.4	17.8	2	15.	23.5	21.9	17.4
1	16.	26.4	24.3	18.4	2	16.	23.3	22.3	17.8
1	17.	23.9	23.0	18.9	2	17.	21.6	21.1	18.0
1	18.	21.8	22.1	19.1	2	18.	19.9	20.1	18.1
1	19.	19.5	20.0	19.1	2	19.	18.4	18.7	18.1
1	20.	17.9	18.6	18.8	2	20.	17.1	17.6	17.9
1	21.	16.9	17.6	18.3	2	21.	16.2	16.7	17.6
1	22.	16.1	16.7	17.6	2	22.	15.6	16.0	17.1
1	23.	15.4	16.1	17.0	2	23.	14.9	15.4	16.7
1	0.	14.9	15.5	16.4	2	0.	14.6	14.9	16.2
1	1.	14.4	15.1	15.9	2	1.	14.1	14.5	15.8
1	2.	14.1	14.7	15.4	2	2.	13.7	14.1	15.4

AVERAGE SOIL TEMPERATURE DATA FROM AMES 5/26/83, CHISEL TREATMENT

REP	HOUR	DEPTH (CM) 2.5	5.0	15.0	REP	HOUR	DEPTH (CM) 2.5	5.0	15.0
1	21.	13.8	15.1	18.2	2	21.	14.5	15.1	18.1
1	22.	12.6	14.1	17.7	2	22.	13.5	14.1	17.7
1	23.	11.7	13.2	17.1	2	23.	12.5	13.3	17.2
1	0.	10.8	12.5	16.6	2	0.	11.7	12.5	16.8
1	1.	10.2	11.8	16.1	2	1.	11.0	11.8	16.4
1	2.	9.5	11.2	15.7	2	2.	10.4	11.2	16.0
1	3.	9.1	10.7	15.2	2	3.	9.9	10.7	15.6
1	4.	8.6	10.3	14.7	2	4.	9.4	10.2	15.2
1	5.	8.2	9.8	14.1	2	5.	8.9	9.8	14.6
1	6.	8.7	9.7	13.5	2	6.	9.2	9.7	14.1
1	7.	10.7	10.4	13.1	2	7.	10.8	10.7	13.6
1	8.	13.3	11.9	12.9	2	8.	12.5	12.1	13.4
1	9.	16.3	13.7	13.2	2	9.	14.9	13.9	13.5
1	10.	20.2	16.3	13.7	2	10.	18.1	16.5	13.8
1	11.	23.7	18.9	14.6	2	11.	21.1	19.1	14.4
1	12.	25.8	21.2	15.5	2	12.	23.4	21.3	15.1
1	13.	26.6	22.4	16.5	2	13.	24.4	22.6	15.9
1	14.	22.2	21.3	17.3	2	14.	22.0	21.5	16.6
1	15.	25.3	21.8	18.0	2	15.	23.6	22.2	17.2
1	16.	25.4	22.5	18.5	2	16.	24.0	22.8	17.7
1	17.	22.9	21.7	18.8	2	17.	22.6	22.1	18.1
1	18.	21.1	20.8	19.0	2	18.	21.4	21.2	18.4
1	19.	19.0	19.3	18.9	2	19.	19.6	19.8	18.5
1	20.	17.6	18.1	18.7	2	20.	18.3	18.6	18.4
1	21.	16.6	17.2	18.2	2	21.	17.4	17.7	18.1
1	22.	15.9	16.6	17.7	2	22.	16.7	16.9	17.7
1	23.	15.2	15.9	17.1	2	23.	15.9	16.3	17.2
1	0.	14.9	15.5	16.6	2	0.	15.4	15.8	16.8
1	1.	14.5	15.1	16.1	2	1.	15.3	15.4	16.4
1	2.	14.1	14.8	15.7	2	2.	14.6	14.9	16.0

AVERAGE SOIL TEMPERATURE DATA FROM AMES 6/7/83, NO-TILL TREATMENT

REP	HOUR	DEPTH (CM) 2.5	5.0	15.0	REP	HOUR	DEPTH (CM) 2.5	5.0	15.0
1	21.	18.1	19.2	24.3	2	21.	17.9	19.2	23.6
1	22.	16.6	17.7	23.1	2	22.	16.7	18.0	22.6
1	23.	15.5	16.5	22.0	2	23.	15.8	17.1	21.7
1	0.	14.6	15.6	21.0	2	0.	15.1	16.3	20.8
1	1.	13.8	14.9	20.1	2	1.	14.4	15.7	20.1
1	2.	13.3	14.3	19.3	2	2.	13.8	15.1	19.4
1	3.	12.8	13.8	18.6	2	3.	13.4	14.6	18.8
1	4.	12.3	13.2	17.9	2	4.	12.9	14.2	18.1
1	5.	11.9	12.8	17.2	2	5.	12.5	13.7	17.5
1	6.	12.4	12.8	16.7	2	6.	13.0	13.7	17.0
1	7.	14.1	13.7	16.3	2	7.	15.4	14.9	16.7
1	8.	16.8	15.6	16.3	2	8.	18.8	17.0	16.8
1	9.	20.3	18.2	16.8	2	9.	22.6	19.7	17.5
1	10.	23.8	21.2	17.6	2	10.	26.1	22.3	18.5
1	11.	27.1	24.1	18.8	2	11.	29.1	24.8	19.8
1	12.	30.2	26.9	20.2	2	12.	31.4	26.9	21.2
1	13.	32.6	29.2	21.6	2	13.	32.9	28.6	22.6
1	14.	34.2	31.0	23.0	2	14.	33.6	29.7	23.8
1	15.	34.5	31.9	24.2	2	15.	33.2	29.7	24.7
1	16.	33.6	31.7	25.2	2	16.	31.5	29.3	25.3
1	17.	32.4	30.9	25.9	2	17.	29.8	28.3	25.6
1	18.	30.3	29.5	26.1	2	18.	27.7	27.0	25.6
1	19.	27.2	27.4	25.9	2	19.	24.9	25.2	25.2
1	20.	23.8	24.6	25.3	2	20.	22.7	23.6	24.5
1	21.	21.1	22.3	24.3	2	21.	20.8	22.0	23.6
1	22.	19.4	20.6	23.1	2	22.	19.5	20.8	22.6
1	23.	18.0	19.2	22.0	2	23.	18.3	19.7	21.7
1	0.	17.0	18.2	21.0	2	0.	17.5	18.9	20.8
1	1.	16.2	17.3	20.1	2	1.	16.8	18.1	20.1
1	2.	15.5	16.5	19.3	2	2.	16.1	17.5	19.4

AVERAGE SOIL TEMPERATURE DATA FROM AMES 6/7/83, PLOW TREATMENT

REP	HOUR	DEPTH (CM)			REP	HOUR	DEPTH (CM)		
		2.5	5.0	15.0			2.5	5.0	15.0
1	21.	18.8	19.9	24.7	2	21.	17.9	18.8	23.2
1	22.	17.4	18.5	23.7	2	22.	16.6	17.5	22.6
1	23.	16.3	17.4	22.8	2	23.	15.6	16.6	21.9
1	0.	15.5	16.5	21.8	2	0.	14.8	15.7	21.2
1	1.	14.7	15.8	21.0	2	1.	14.1	14.9	20.6
1	2.	14.0	15.1	20.3	2	2.	13.6	14.5	20.0
1	3.	13.4	14.5	19.6	2	3.	13.0	13.9	19.5
1	4.	12.9	13.9	19.0	2	4.	12.5	13.4	18.9
1	5.	12.5	13.4	18.3	2	5.	12.2	12.9	18.3
1	6.	12.8	13.4	17.7	2	6.	12.9	13.2	17.8
1	7.	13.9	14.1	17.2	2	7.	15.3	14.5	17.5
1	8.	16.3	15.7	17.1	2	8.	18.5	16.7	17.3
1	9.	19.5	18.1	17.3	2	9.	22.1	19.5	17.5
1	10.	22.9	20.9	17.8	2	10.	25.3	22.4	18.0
1	11.	26.3	23.8	18.7	2	11.	27.9	25.0	18.8
1	12.	29.4	26.6	19.9	2	12.	30.1	27.2	19.8
1	13.	32.1	28.9	21.1	2	13.	31.5	28.9	20.7
1	14.	33.9	30.9	22.4	2	14.	32.3	29.9	21.7
1	15.	34.3	31.8	23.6	2	15.	31.9	30.0	22.5
1	16.	33.8	31.9	24.7	2	16.	30.7	29.5	23.2
1	17.	32.7	31.4	25.5	2	17.	28.9	28.5	23.6
1	18.	30.9	30.1	25.9	2	18.	27.1	26.9	23.9
1	19.	27.7	28.0	25.9	2	19.	24.9	25.2	23.9
1	20.	24.5	25.4	25.4	2	20.	22.8	23.4	23.6
1	21.	22.1	23.2	24.7	2	21.	20.8	21.7	23.2
1	22.	20.4	21.6	23.7	2	22.	19.4	20.3	22.6
1	23.	19.1	20.2	22.8	2	23.	18.1	19.1	21.9
1	0.	17.9	19.2	21.8	2	0.	17.3	18.2	21.2
1	1.	17.0	18.2	21.0	2	1.	16.4	17.4	20.6
1	2.	16.2	17.4	20.3	2	2.	15.7	16.6	20.0

AVERAGE SOIL TEMPERATURE DATA FROM AMES 6/7/83, CHISEL TREATMENT.

		DEPTH (CM)					DEPTH (CM)		
REP	HOUR	2.5	5.0	15.0	REP	HOUR	2.5	5.0	15.0
1	21.	17.4	18.6	22.8	2	21.	16.8	20.0	23.2
1	22.	16.3	17.6	22.1	2	22.	15.8	18.8	22.5
1	23.	15.6	16.8	21.3	2	23.	15.2	17.8	21.8
1	0.	14.9	16.1	20.6	2	0.	14.5	17.0	21.1
1	1.	14.2	15.6	20.0	2	1.	14.1	16.2	20.5
1	2.	13.7	15.0	19.4	2	2.	13.6	15.7	19.9
1	3.	13.3	14.6	18.9	2	3.	13.2	15.1	19.4
1	4.	12.8	14.2	18.3	2	4.	12.8	14.5	18.8
1	5.	12.6	13.8	17.8	2	5.	12.4	14.1	18.3
1	6.	12.8	13.7	17.3	2	6.	12.6	14.0	17.8
1	7.	14.2	14.1	16.9	2	7.	14.4	14.7	17.4
1	8.	16.6	15.4	16.8	2	8.	16.9	16.3	17.2
1	9.	19.8	17.3	16.9	2	9.	19.5	18.5	17.2
1	10.	22.9	19.5	17.4	2	10.	22.3	21.0	17.5
1	11.	25.9	21.8	18.1	2	11.	26.7	23.5	18.1
1	12.	28.6	24.1	19.1	2	12.	28.8	25.9	19.0
1	13.	30.3	25.8	20.1	2	13.	31.9	27.9	19.9
1	14.	31.7	27.1	21.2	2	14.	32.6	29.3	20.9
1	15.	31.7	27.8	22.1	2	15.	32.3	29.9	21.9
1	16.	30.6	27.7	22.9	2	16.	31.3	29.9	22.7
1	17.	29.2	27.2	23.5	2	17.	30.6	29.3	23.4
1	18.	27.3	26.2	23.7	2	18.	28.7	28.1	23.7
1	19.	24.5	24.5	23.7	2	19.	24.6	26.6	23.8
1	20.	22.1	22.9	23.4	2	20.	22.9	24.8	23.6
1	21.	20.3	21.4	22.8	2	21.	20.8	23.2	23.2
1	22.	18.9	20.2	22.1	2	22.	18.9	21.8	22.5
1	23.	17.9	19.3	21.3	2	23.	18.2	20.6	21.8
1	0.	17.1	18.4	20.6	2	0.	17.4	19.6	21.1
1	1.	16.5	17.8	20.0	2	1.	16.8	18.8	20.5
1	2.	15.8	17.2	19.4	2	2.	15.5	17.9	19.9

APPENDIX B. SOIL TEMPERATURE VALUES FOR SELECTED DATES FOR VARYING SOIL SURFACE ROUGHNESS CONDITIONS

Tillage code: treatment 1 = plow

treatment 2 = disk

treatment 3 = disk-disk

treatment 4 = roll

AVERAGE SOIL TEMPERATURE DATA, 8/2/83

TRT	HOUR	DEPTH (CM) 1.0	5.0	15.0	TRT	HOUR	DEPTH (CM) 1.0	5.0	15.0
1	-3.	24.8	24.6	27.0	2	-3.	24.7	25.2	26.6
1	-2.	23.5	23.7	26.4	2	-2.	23.4	24.3	26.2
1	-1.	22.4	22.9	26.0	2	-1.	22.5	23.4	25.8
1	0.	21.5	22.3	25.5	2	0.	21.6	22.8	25.4
1	1.	20.8	21.7	25.0	2	1.	20.9	22.1	25.0
1	2.	19.9	21.0	24.6	2	2.	20.1	21.5	24.7
1	3.	19.2	20.4	24.2	2	3.	19.4	20.9	24.3
1	4.	18.6	19.9	23.7	2	4.	19.0	20.4	23.9
1	5.	18.1	19.4	23.3	2	5.	18.4	19.9	23.6
1	6.	18.0	19.3	22.9	2	6.	18.6	19.6	23.2
1	7.	19.4	21.3	22.6	2	7.	20.5	20.4	22.9
1	8.	22.9	23.9	22.4	2	8.	24.3	22.3	22.6
1	9.	25.8	25.9	22.4	2	9.	28.1	24.6	22.3
1	10.	30.0	27.9	22.6	2	10.	32.1	27.5	22.5
1	11.	34.1	30.1	23.2	2	11.	36.0	30.2	23.0
1	12.	37.3	31.5	23.9	2	12.	38.4	32.5	23.7
1	13.	40.3	32.3	24.7	2	13.	41.2	33.8	23.9
1	14.	40.4	32.8	26.2	2	14.	41.7	35.2	25.5
1	15.	41.0	31.8	27.2	2	15.	41.3	35.2	26.4
1	16.	39.8	31.8	27.7	2	16.	40.1	33.9	26.3
1	17.	38.3	31.3	28.6	2	17.	37.8	32.8	27.6
1	18.	35.3	30.2	28.9	2	18.	34.3	31.4	28.0
1	19.	31.8	34.0	29.0	2	19.	27.8	29.8	28.2
1	20.	29.0	27.9	28.8	2	20.	28.8	28.4	28.1
1	21.	27.0	26.5	28.4	2	21.	26.8	27.1	27.8
1	22.	25.6	25.7	27.9	2	22.	25.5	26.0	27.4
1	23.	24.4	24.8	27.3	2	23.	24.4	25.1	27.0
1	24.	23.5	24.2	26.9	2	24.	23.7	24.4	26.6
1	25.	22.8	23.5	26.3	2	25.	22.9	23.8	26.1
1	26.	22.1	22.8	25.8	2	26.	22.1	23.3	25.7

AVERAGE SOIL TEMPERATURE DATA, 8/2/83

TRT	HOUR	DEPTH (CM) 1.0	5.0	15.0	TRT	HOUR	DEPTH (CM) 1.0	5.0	15.0
3	-3.	24.6	26.4	28.0	4	-3.	25.5	28.3	29.4
3	-2.	23.3	25.3	27.5	4	-2.	24.0	26.9	28.9
3	-1.	22.4	24.3	27.0	4	-1.	22.9	25.7	28.3
3	0.	21.4	23.5	26.5	4	0.	21.9	24.8	27.9
3	1.	20.6	22.7	25.9	4	1.	21.0	23.8	27.3
3	2.	19.8	22.0	25.5	4	2.	20.1	23.0	26.8
3	3.	19.2	21.3	25.0	4	3.	19.3	22.2	26.4
3	4.	18.6	20.7	24.5	4	4.	18.7	21.6	25.9
3	5.	18.1	20.2	24.1	4	5.	18.2	21.0	25.4
3	6.	18.4	19.9	23.7	4	6.	18.5	20.6	25.1
3	7.	21.7	21.1	23.3	4	7.	21.6	21.4	24.6
3	8.	26.1	23.6	23.2	4	8.	26.3	23.4	24.4
3	9.	29.8	26.5	23.3	4	9.	30.9	26.3	24.3
3	10.	34.0	29.5	23.7	4	10.	35.7	29.6	24.6
3	11.	37.7	32.4	24.3	4	11.	39.9	32.9	25.2
3	12.	40.3	34.7	25.3	4	12.	42.9	35.7	26.0
3	13.	42.7	35.9	26.5	4	13.	44.5	37.5	26.9
3	14.	42.6	37.7	27.7	4	14.	46.4	39.6	28.1
3	15.	41.9	38.0	28.8	4	15.	45.8	40.2	29.1
3	16.	40.3	37.4	29.5	4	16.	44.2	39.9	29.6
3	17.	37.6	36.3	30.1	4	17.	42.2	39.4	30.7
3	18.	34.1	34.5	30.4	4	18.	38.2	37.7	31.1
3	19.	31.0	32.2	30.4	4	19.	33.6	35.2	31.4
3	20.	28.6	30.2	30.0	4	20.	30.1	32.7	31.2
3	21.	26.6	28.5	29.5	4	21.	27.8	30.6	30.8
3	22.	25.3	27.2	29.0	4	22.	26.2	29.0	30.3
3	23.	24.3	26.1	28.3	4	23.	25.1	27.7	29.8
3	24.	23.5	25.3	27.8	4	24.	24.1	26.7	29.2
3	25.	22.8	24.5	27.3	4	25.	23.3	25.9	28.7
3	26.	22.2	23.9	26.8	4	26.	22.7	25.1	28.2

AVERAGE SOIL TEMPERATURE DATA, 7/26/83

TRT	HOUR	DEPTH (CM) 1.0	5.0	15.0	TRT	HOUR	DEPTH (CM) 1.0	5.0	15.0
1	-3.	25.4	25.0	26.1	2	-3.	25.2	25.0	25.4
1	-2.	24.1	24.2	25.8	2	-2.	24.0	24.2	25.2
1	-1.	23.1	23.4	25.5	2	-1.	23.0	23.4	25.0
1	0.	22.3	22.8	25.3	2	0.	22.2	22.8	24.7
1	1.	21.5	22.1	24.9	2	1.	21.5	22.2	24.4
1	2.	20.8	21.5	24.5	2	2.	20.9	21.6	24.1
1	3.	20.3	21.1	24.2	2	3.	20.4	21.3	23.9
1	4.	19.8	20.6	23.8	2	4.	19.9	20.8	23.5
1	5.	19.4	20.2	23.5	2	5.	19.6	20.5	23.3
1	6.	19.5	20.3	23.1	2	6.	19.9	20.4	23.0
1	7.	21.2	22.0	22.9	2	7.	21.8	21.1	22.8
1	8.	23.8	24.8	22.7	2	8.	24.1	22.6	22.6
1	9.	27.1	27.8	22.7	2	9.	27.5	24.6	22.6
1	10.	30.4	30.2	23.0	2	10.	30.8	27.0	22.7
1	11.	32.6	30.8	23.4	2	11.	32.0	28.7	23.2
1	12.	35.1	32.5	24.0	2	12.	35.4	30.3	23.6
1	13.	36.0	31.9	24.7	2	13.	35.5	31.2	24.1
1	14.	37.7	31.9	25.2	2	14.	36.7	32.1	24.6
1	15.	36.5	30.5	25.9	2	15.	35.4	31.3	25.1
1	16.	35.5	29.5	26.3	2	16.	33.9	30.4	25.5
1	17.	35.0	28.9	26.5	2	17.	33.7	29.6	25.7
1	18.	32.9	28.0	26.7	2	18.	31.5	28.5	25.9
1	19.	30.3	27.1	26.8	2	19.	29.2	27.5	26.0
1	20.	27.6	26.1	26.7	2	20.	26.9	26.3	25.9
1	21.	25.9	25.0	26.6	2	21.	25.3	25.3	25.8
1	22.	24.6	24.2	26.2	2	22.	24.1	24.4	25.5
1	23.	23.5	23.4	25.9	2	23.	23.2	23.7	25.2
1	24.	22.6	22.8	25.6	2	24.	22.3	23.0	24.9
1	25.	21.8	22.1	25.2	2	25.	21.6	22.4	24.6
1	26.	21.3	21.5	24.7	2	26.	21.2	21.9	24.3

AVERAGE SOIL TEMPERATURE DATA, 7/26/83

		DEPTH (CM)					DEPTH (CM)		
TRT	HOUR	1.0	5.0	15.0	TRT	HOUR	1.0	5.0	15.0
3	-3.	24.8	26.3	26.8	4	-3.	26.1	28.4	28.1
3	-2.	23.5	25.2	26.4	4	-2.	24.6	27.0	27.7
3	-1.	22.5	24.2	26.0	4	-1.	23.4	25.9	27.3
3	0.	21.7	23.5	25.7	4	0.	22.5	25.0	26.9
3	1.	20.9	22.7	25.2	4	1.	21.6	24.1	26.5
3	2.	20.3	22.2	24.9	4	2.	20.9	23.4	26.1
3	3.	19.8	21.7	24.6	4	3.	20.4	22.8	25.7
3	4.	19.3	21.2	24.2	4	4.	19.8	22.2	25.3
3	5.	19.1	20.8	23.9	4	5.	19.5	21.7	25.0
3	6.	19.6	20.7	23.6	4	6.	20.2	21.5	24.6
3	7.	22.3	21.6	23.3	4	7.	23.0	22.2	24.3
3	8.	25.8	23.5	23.2	4	8.	26.3	23.8	24.1
3	9.	29.9	26.0	23.3	4	9.	30.7	26.1	24.1
3	10.	33.5	28.6	23.7	4	10.	34.8	28.7	24.4
3	11.	34.7	30.5	24.2	4	11.	36.3	31.1	25.0
3	12.	38.4	32.0	24.9	4	12.	40.7	32.8	25.5
3	13.	38.1	33.0	25.5	4	13.	40.6	34.2	26.2
3	14.	39.4	33.9	26.1	4	14.	42.6	35.6	27.0
3	15.	37.1	33.2	26.7	4	15.	40.4	35.5	27.7
3	16.	35.2	32.4	27.1	4	16.	38.4	35.0	28.2
3	17.	34.1	31.8	27.3	4	17.	38.1	34.6	28.5
3	18.	31.6	30.7	27.4	4	18.	35.2	33.6	28.8
3	19.	29.0	29.2	27.4	4	19.	31.5	32.0	28.9
3	20.	26.5	27.7	27.2	4	20.	28.2	30.1	28.8
3	21.	24.9	26.3	26.9	4	21.	26.2	28.5	28.5
3	22.	23.6	25.3	26.6	4	22.	24.8	27.2	28.2
3	23.	22.6	24.4	26.2	4	23.	23.6	26.1	27.8
3	24.	21.7	23.7	25.8	4	24.	22.5	25.1	27.3
3	25.	21.1	22.9	25.4	4	25.	21.8	24.3	26.8
3	26.	20.6	22.4	25.1	4	26.	21.2	23.7	26.5

APPENDIX C. FORTRAN PROGRAM USED TO CALCULATE THE SOIL THERMAL DIFFUSIVITY AND SOIL HEAT FLUX

This program calculates the apparent thermal diffusivity (alpha) from measured soil temperature values at two depths. Soil heat flux may be calculated if soil volumetric heat capacity is known. If soil heat flux is not needed, delete the heat flux section.

```
// EXEC FORTG,REGION.GO=320K
//FORT.SYSIN DD *
       IMPLICIT REAL*8(A-H,O-V)
       DIMENSION A(300,27),AT(27,300),DATA(300,27),C(2,2),CC(2,2),V(300)
       DIMENSION E(27,27),F(27),D(27,27),X(1000),Y(1000),X1(300),Y1(300)
       DIMENSION AMP(20),PHASE1(20),PHASE2(20),LOC(20)
       REAL*8 MM,NN
       L=1
       MM=1.
       T=1.
       PI=DATAN(T)*4.0
       DNOM=24.
C      N=NUMBER OF DATA POINTS, M=(2*HARMONICS+1), DZ=DEPTH INCREMENT.
       READ(5,1) N,M,DZ
        III=1
C      CHANGE IF STATEMENT TO NUMBER OF PLOTS
113     IF(III.GT.8)STOP
C      LOC = PLOT IDENTIFIER
        READ(5,111)LOC
111     FORMAT(20A2)
        WRITE(6,112)LOC
112     FORMAT('1',10X,20A2)
       WRITE(6,1)   N,M,DZ
    1  FORMAT(2I3,F4.1)
       READ(5,2) ((DATA(I,J),J=1,3),I=1,N)
C      DATA(I,1)=TIME,DATA(I,2)=UPPER BOUNDRY TEMPERATURE,
C      DATA(I,3)=LOWER BOUNDRY TEMPERATURE
    2  FORMAT(3X,F4.1,F7.1,7X,F7.1)
       WRITE(6,9) ((DATA(I,J),J=1,3),I=1,N)
    9  FORMAT(1H0,3F6.2)
       DO 13 I=1,N
   13  A(I,1)=1.
       SUM=0.
       DO 14 I=1,N
       X1(I)=DATA(I,1)
       Y1(I)=DATA(I,2)
       V(I)=DATA(I,2)
       SUM=SUM+DATA(I,2)
       NN=MM
       DO 14 J=3,M,2
       A(I,J)=DSIN((NN)*PI*2.*X1(I)/DNOM)
       A(I,J-1)=DCOS((NN)*PI*2.*X1(I)/DNOM)
       NN=NN+MM
```

```
   14  CONTINUE
       XBAR=SUM/N
       WRITE(6,6) XBAR
       DO 15 I=1,N
   15  A(I,1)=XBAR
       DO 4 I=1,N
       DO 4 J=1,M
    4  AT(J,I)=A(I,J)
       CALL MATMPY(AT,A,E,M,N,M)
       CALL MATMPY(AT,V,D,M,N,L)
       DO 16 I=1,M
   16  E(I,M+1)=D(I,1)
       CALL GAUSS(E,M,F)
       X(1)=0.
       Y(1)=0.
       Z=DATA(N,1)
       DO 5 I=1,801
       X(I)=(I-1)*(Z/800)
       TERM=0.
       NN=MM
       DO 8 J=3,M,2
       TERM=TERM+F(J)*DSIN((NN)*PI*2.*X(I)/DNOM)
       TERM=TERM+F(J-1)*DCOS((NN)*PI*2.*X(I)/DNOM)
       NN=NN+MM
    8  CONTINUE
       TERM=TERM+F(1)*XBAR
    5  Y(I)=TERM
       WRITE(6,6) (F(I),I=1,M)
    6  FORMAT(1H0,F16.10)
       L=0
       DO 17 I=3,M,2
       L=L+1
       AMP((I-1)/2)=DSQRT(F(I)*F(I)+F(I-1)*F(I-1))
       PHASE1((I-1)/2)=DATAN(F(I-1)/F(I))
       PHASE2((I-1)/2)=DARSIN(F(I-1)/AMP((I-1)/2))
       CHECK=DABS(PHASE1((I-1)/2)-PHASE2((I-1)/2))
       IF(CHECK.GT..02) PHASE1((I-1)/2)=PHASE1((I-1)/2)+PI
       IF(CHECK.LT..02.AND.PHASE1((I-1)/2.).LT.0.) PHASE1((I-1)/2.)=
      1 2*PI-PHASE1((I-1)/2)
       WRITE(6,19) AMP((I-1)/2),PHASE1((I-1)/2),PHASE2((I-1)/2)
       AMP(L)=AMP((I-1)/2)
   17  PHASE1(L)=PHASE1((I-1)/2)
   30  FORMAT(1H0,2F10.4)
        IHAR=(M-1)/2
       TEST=100000.
       ALPHA= 3.
       DELT=1.00
C 200  ALPHA=ALPHA+DELT
       SUM=0.
       DO 300 I=1,N
```

```
      X(I)=DATA(I,1)
      Y(I)=DATA(I,3)
  300 SUM=SUM+DATA(I,3)
      XBAR=SUM/N
      WRITE(6,6) XBAR
      WRITE(6,68)
   68 FORMAT(1H0,'   ALPHA        SSQ')
  200 ALPHA=ALPHA+DELT
      SSQ=0.
      DO 400 I=1,N
      EST=XBAR
      NN=0.
      DO 500 J=1,IHAR
      NN=NN+MM
      TERM=-DZ*DSQRT(NN*PI/(DNOM*ALPHA))
  500 EST=EST+DEXP(TERM)*DSIN((NN*2.*PI*X(I)/DNOM)+PHASE1(J)+TERM)
     $*AMP(J)
  400 SSQ=SSQ+(EST-Y(I))**2
      IF(TEST-SSQ) 31,31,22
   31 IF(DELT.LE.0.011)GO TO 21
      ALPHA=ALPHA-(2*DELT)
      DELT=DELT/10.
      TEST=100000.
      GO TO 200
   21 ALPHA=ALPHA-DELT
      WRITE(6,67)
   67 FORMAT(1H0,'  ALPHA (CM**2/HOUR)')
C       ALPHA IS PRINTED IN (CM**2/HOUR)
      WRITE(6,6) ALPHA
      GO TO 26
   22 TEST=SSQ
      WRITE(6,66)ALPHA,SSQ
   66 FORMAT(1H ,F10.2,F10.4)
      IF(ALPHA.GT.30.) STOP
      GO TO 200
   26 Z=X(N)
      DO 27 I=1,801
      X(I)=(I-1)*(Z/800)
      NN=MM
      TT=XBAR
      DO 28 J=1,IHAR
      TERM=-DZ*DSQRT(NN*PI/(DNOM*ALPHA))
      TT=TT+DEXP(TERM)*DSIN((NN*2.*PI*X(I)/DNOM)+PHASE1(J)+TERM)
     $*AMP(J)
   28 NN=NN+MM
   27 Y(I)=TT
   19 FORMAT(1H0,3F10.4)
        III=III+1
C       THIS SECTION CALCULATES AND PRINTS SOIL HEAT FLUX
C       READ VOLUMETRIC HEAT CAPACITY (CAL/CC K), SOIL DEPTH
```

```
C            PAST UPPER BOUNDRY TEMPERATURE (CM)
      READ(5,45) CV,Z
      PRINT 46,CV,Z
46    FORMAT(' VOL. HEAT CAP. = ',F9.4,'DEPTH = ',F9.2)
45    FORMAT(' ',F5.4,F4.2)
      ALPHA=ALPHA/60.
      OMEGA=0.00436
C     OMEGA=ANGULAR FREQUENCY
C     CALCULTION LOOPS
      T=0.0
      DO 42 J=1,24
      G(J)=0.0
      KK=(M-1)/2.
      DO 41 N=1,KK
      TERM1=AMP(N)*CV*DSQRT(N*ALPHA*OMEGA)
      TERM2=DEXP(-Z*DSQRT((N*OMEGA)/(2*ALPHA)))
      TERM3=DSIN((N*OMEGA*T)+PHASE1(N)+0.7854
     $       -(Z*DSQRT((N*OMEGA)/(2*ALPHA))))
      TERM4=TERM1*TERM2*TERM3
      G(J)=G(J)+TERM4
41    CONTINUE
      T=T+60
42    CONTINUE
      PRINT 36
36    FORMAT(' HOUR     SOIL HEAT FLUX (CAL/CM**3 C MIN)')
      PRINT 35,(J,G(J),J=1,24)
35    FORMAT(' ',I3,3X,F12.7)
     GO TO 113
69    STOP
      END
C
C
C
      SUBROUTINE MATMPY(A,B,C,M,N,L)
C***MATRIX C IS PRODUCT OF A AND B MATRICES***
       IMPLICIT REAL*8(A-H,O-V)
      DIMENSION A(27,300),B(300,27),C(27,27)
      DO 20 I=1,M
      DO 20 J=1,L
      C(I,J)=0.
      DO 20 K=1,N
   20 C(I,J)=C(I,J)+A(I,K)*B(K,J)
      RETURN
      END
C
C
C
C***SOLUTION OF SIMULTANEOUS EQUATIONS BY GAUSSIAN ELIMINATION***
      SUBROUTINE GAUSS(A,N,F)
      IMPLICIT REAL*8(A-H,O-V)
```

```
      DIMENSION A(27,27),F(27)
   57 FORMAT(1H0,7(2X,F12.8))
    3 FORMAT(I3)
      M=N+1
      L=N-1
      II=0
    4 FORMAT(13F5.0)
      DO 12 K=1,L
      JJ=K
      BIG=DABS(A(K,K))
      KP1=K+1
C
C***SEARCH FOR LARGEST POSSIBLE PIVOT ELEMENT***
      DO 7 I=KP1,N
      AB=DABS(A(I,K))
      IF(BIG-AB) 6,7,7
    6 BIG=AB
      JJ=I
    7 CONTINUE
C
C***DECISION ON NECESSITY OF ROW EXCHANGE***
      IF(JJ-K) 8,10,8
C
C***ROW EXCHANGE***
    8 DO 9 J=K,M
      TEMP=A(JJ,J)
      A(JJ,J)=A(K,J)
    9 A(K,J)=TEMP
      II=II+1
C
C***CALCULATION OF ELEMENTS OF NEW MATRIX***
   10 DO 11 I=KP1,N
      QUOT=A(I,K)/A(K,K)
      DO 11 J=KP1,M
   11 A(I,J)=A(I,J)-QUOT*A(K,J)
      DO 12 I=KP1,N
   12 A(I,K)=0.
C     DET=(-1)**II*DIAG(A,N)
C
C***FIRST STEP IN BACK SUBSTITUTION***
      F(N)=A(N,M)/A(N,N)
C
C***REMAINDER OF BACK SUBSTITUTION PROCESS***
      DO 14 NN=1,L
      SUM=0.
      I=N-NN
      IP1=I+1
      DO 13 J=IP1,N
   13 SUM=SUM+A(I,J)*F(J)
   14 F(I)=(A(I,M)-SUM)/A(I,I)
```

```
    2 FORMAT(1H ,E19.8)
   23 FORMAT(1H0,E14.8)
      RETURN
      END
//GO.SYSIN DD *
```